Saskatchewan
Environment and
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Mines Pollution
Control Branch

# Mine Rock Guidelines

## Design and Control of Drainage Water Quality

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Saskatchewan Environment and Public Safety
Mines Pollution Control Branch

Report 93301

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# Design and Control of Drainage Water Quality

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**REPORT NO. 93301**

# MINE ROCK GUIDELINES DESIGN AND CONTROL OF DRAINAGE WATER QUALITY

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# MINE ROCK GUIDELINES DESIGN AND CONTROL OF DRAINAGE WATER QUALITY

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# 1.0 INTRODUCTION

## 1.1 Objectives of the Guide

The objectives of this Draft Guide are to provide a summary of the processes which control drainage water quality from mine rock (waste rock) piles in Saskatchewan and to provide the user with guidance and recommendations for the state of the art in prediction, control and monitoring of acid rock drainage (ARD) and metal leaching. This document has been prepared as a draft with the intention that it will be a working reference for industry, regulatory authorities, and researchers. As the Guide is used over the next two to three years, and the database of information in the province develops, the Guide should be updated where necessary.

The recommendations and conclusions that have been made are with particular reference to the uranium mining industry in Saskatchewan, although the general philosophy and technical approach are used throughout the mining industry. This Guide is a summary document, and specific technical references are cited throughout. If more information is required in a specific area, the reader is encouraged to refer to the references.

## 1.2 Background

This Guide was prepared for Saskatchewan Environment and Public Safety, Mines Pollution Control Branch (MPCB) based on a discussion paper prepared by the Branch in December, 1990, with the following introduction:

> Waste rock is the by-product of virtually all mining activities in Northern Saskatchewan. Particularly at open pit mines, which comprise the majority of uranium mines in Saskatchewan, the tonnage of waste rock generated... exceed[s] the tonnage of ore removed during the life of the mine. Obviously, with these volumes, the proper handling and disposal of waste rock, especially from a decommissioning and abandonment viewpoint, is of significant environmental importance.

> The term "waste rock" as applied to mining, is a vague description, meaning only "rock which had to be removed from a place to permit mining of ore, but which in itself is of no economic value". As such, it may vary from overlying unconsolidated material (although this is typically known as overburden) to rock of similar nature to the ore, but too low grade for the sought after mineral to economically justify processing.

There is a conscious effort in the industry to replace the terms "waste rock" and "waste rock piles" with mine rock and mine rock piles. The latter terms have been adopted for this guide to differentiate these materials from hazardous or special waste rock.

Mine rock is generated throughout the mining process and remains on site long after mining operations cease. Such mine rock, with its associated sub-economic mineralization, is exposed to the environment and the natural processes of oxidation, biological activity and leaching by infiltration water with its dissolved constituents. Natural leaching of the contained minerals occurs; a process which can be accelerated by a number of natural processes including acid generation. Such leaching and flushing, with or without acid generation, can carry deleterious substances downstream into the receiving environment. Readily leachable constituents may appear in drainage water within weeks or months of deposition. For those mine rock deposits which ultimately become acid generating the acid drainage and metal leaching (without acid generation) to drainage water may not become apparent for many years, but once initiated can continue for hundreds of years. When produced in high volumes, particularly from open pit operations, contaminant leaching and acid generating mine rock can require extensive control and remediation measures to prevent adverse environmental impacts. As recognized by the MPCB, there are a number of physical, chemical, geochemical and biological factors which influence the potential for contaminant release from a sample, and which therefore influence the technology for prediction and handling of such rock. Appropriate mine rock management plans for handling and control of drainage water quality can only be developed with the proper classification of the material and an understanding of the current technology for prediction of drainage water quality.

## 1.3 Structure of the Guide

This guide is intended to be a working document for regulatory agencies, industry, and researchers and scientists in the uranium mining industry. Each chapter addresses a specific aspect of drainage water quality from mine rock piles: from identifying potential sources of contaminants, through developing control measures, evaluating options and monitoring the effectiveness of the control measures. Each chapter is intended to be "stand-alone" and summarizes the current state-of-practice while citing more detailed reference literature for specific topics. A list of key references is provided in Chapter 10.

Table 1.1 summarizes the technology presented in the guide and is reproduced in Chapter 8 which discusses closure and long term control through each of the steps necessary to assess mine rock and the potential drainage water quality to develop sound mine rock management strategies both for during operation and for closure. The "level of effort" which each step requires will depend on the stage of operation. This is indicated by the marker in each column of Table 1.1. Key tables and figures from each chapter are noted also in this table.

## 1.4 Brief History of ARD

Contaminated drainage from metal mines results from the flushing of metals which are readily soluble as a result of geologic processes and conditions of formation. Dissolution and leaching of other metals is accelerated by oxidation of sulphidic minerals. The oxidation of mineral sulphides when exposed to air and water results in the production of acidity and increased leaching of contaminants, particularly heavy metals. This increase in contaminant load increases the potential for environmental impact.

The history of ARD was summarized in SRK et al.(1989):

> Acid rock drainage has likely been experienced from mines since mining started. Paine (1987) points out that a document summarizing available mining and smelting technology, written by Georgius Agricola and published in 1556, probably contains the first reference to environmental impacts of ARD. In countries such as Norway, which have been major miners and producers of copper

TABLE 1.1

**Summary Guide to Site Assessment and Management Plan Development**

| SUBJECT<br>STAGES IN PLAN DEVELOPMENT | APPLICABLE TO: | | | APPROPRIATE SECTION OF GUIDE |
|---|---|---|---|---|
| | NEW MINE | EXISTING MINE | CLOSED MINE | |
| Understanding of Acid Generation | ● | ● | ● | 1,2,3 |
| Understanding of Metal Leaching | ● | ● | ● | 1,2,3 |
| Definition of Pre-development Environment | ● | ● | ○ | 7.1 |
| Definition of Development | ● | ● | ● | |
| Site Assessment - Field Investigations | • | ● | ● | 4 |
| Contaminant Release Prediction | | | | |
| - ARD | ● | ○ | • | 5 |
| - Contaminant Leaching | ● | ○ | • | 5 |
| Control Measures Selection and Design | | | | |
| - Subaqueous deposition | ● | ○ | • | 6.2.4 |
| - Covers | ● | ● | ● | 6.2.3 |
| - Others | ○ | ○ | • | 6 |
| Modelling | ● | ● | ○ | 7 |
| Closure Plan Preparation | ● | ● | ● | 8 |
| Monitoring | | | | |
| - Surface water | ● | ● | ● | 9 |
| - Groundwater | ○ | ● | ● | |
| - Mine rock/tailings | - | ● | ● | |
| - Sediments | • | ● | ● | 4.3.6 |
| - Biological | ● | ● | ● | 4.3.7 |
| - Seeps | - | ● | ● | 4.3.2 |
| - Control Structures | - | ● | ● | |
| - Climate | ● | ● | ● | |

Key: ● Required at comprehensive level.
○ Generally required at intermediate level.
• May be required; usually at low or intermediate level.

> and sulphide concentrates for the industrialized world for over 300 years, ARD has occurred extensively, continuously and in close association with human habitation for centuries (NIVA, 1987). The effect of ARD on man himself is limited but the impact on the aquatic environment can be large. In Norway, little control has been exercised in the prevention of ARD. From a total of thirty-one metal mines there has been minor environmental effects at fourteen, significant effects at three, and severe effects (resulting in the loss of a number of tens of kilometres of fish habitat in receiving waters) at three. In Australia, ARD from waste rock at an abandoned uranium mine was principally responsible for the loss of aquatic fauna for some nine kilometres of the Finniss River in the Northern Territory (NTDME, 1986).

In Canada, the mining history is relatively short compared to countries such as Norway and Sweden with over a thousand years of mining history. Nevertheless, metal laden, acidic drainage has caused significant environmental impacts at a number of mine sites, and is a significant concern in several provinces including B.C., Ontario, New Brunswick and the Yukon. The technology for prediction and control of metal leaching and ARD has developed significantly over the past ten years, spurred by general industry and government concern which has lead to the coordination of research through groups such as the B.C. Acid Mine Drainage Task Force and the Mine Environment Neutral Drainage Committee. In the uranium mining areas of northern Saskatchewan ARD does not appear to be as severe or extensive at this time as in the sulphide-rich base metal deposits of other areas of Canada. However, leaching of readily soluble constituents is currently a concern for many sites. Thus, standard practices for development of mine rock management plans, which can be applied to uranium mining in Saskatchewan, have not as yet been developed to a stage where they may be considered to be established technology. The Draft Acid Rock Drainage Technical Guide provides some suggested practices specific to ARD and metal leaching, but these must be modified and extended to be of optimal benefit to the Saskatchewan conditions.

# 2.0 SASKATCHEWAN URANIUM MINES

## 2.1 General

The uranium mining area of Saskatchewan is located in the northern half of the province within the Athabasca basin. This is a relatively flat-lying area with subdued regional relief and a seasonal northern climate. Climate and topography will affect the nature and extent of contaminated drainage, the impact of the drainage, appropriate control measures, and design of water quality monitoring programs. While each site will have unique climatic conditions, there are a number of common features:

- relatively low precipitation (300-550 mm/year), approximately 30% of which occurs as snow, with up to 400 mm evapotranspiration and very low levels of runoff. The spring freshet period, and extent of flushing of the rock pile will depend on the snowpack and melting period;
- periods of heavy rain in late summer or fall at some sites, although others, such as the Key Lake have near-desert conditions with less than 300 mm annual precipitation and high evapotranspiration rates of >300 mm/year;
- migration of contaminants will be influenced by precipitation/climate;
- long winter extending from October to June in which water sampling would be very limited;
- freezing of localized areas within rock piles, although some venting of hot air has been noted in piles containing oxidizing material;
- freeze-thaw cycles induce physical breaking and slaking of material which increases the exposed rock surface area;
- muskeg and bog areas which, in some seasons, may provide periodic chemical and physical attenuation of contaminated drainage flow.

## 2.2 Regulatory Requirements

Until now, there have been no specific guidelines in Saskatchewan for the characterization of mine rock, nor for handling and management of the various types of mine rock for control of drainage water quality. While each site assessment must be based on the specific site and mine

plan, a general guide and recommendations for an approach to assessment and control is presented in this guide.

The necessary level of control of mine rock drainage water quality is generally determined by objectives for surface water quality which are incorporated into the environmental review prior to development or operational approval. Mine water discharge quality limits are defined for specific parameters in the federal Metal Mining Liquid Effluent Regulations and Guidelines (EPS 1-WP-77-1, 1984). Guidelines for site receiving water quality are presented in the document entitled "Surface Water Quality Objectives" prepared by Saskatchewan Environment and Public Safety, Water Quality Branch, Document WQ 110 (November 1988) for the protection of aquatic life and wildlife. These specific surface water guidelines do not include uranium or radionuclides; however, in the Saskatchewan General Surface Water Quality Objectives, the Radium 226 value is 0.11 Bq/L. Objectives for protecting the quality of the habitat of aquatic organisms (including fish, aquatic fauna and flora) are often more stringent than those applicable to other water uses. These objectives will afford a reasonable degree of protection of fish and other aquatic life at all stages of development. Because of the relatively stringent values for various constituents these objectives will also likely afford protection to wildlife which rely upon surface water for drinking water and for their source of food supply. A portion of these objectives is summarized in Table 2.1.

## 2.3 Existing Data

### 2.3.1 Water Quality and Acid Generation Potential

The mining history in northern Saskatchewan is relatively short.

The leaching of metals into drainage water as a result of natural solubility, or leaching enhanced by oxidation and acid generation, has been recognized at several sites from monitoring during operation. Sites where the drainage water quality is a concern have generally incorporated drainage water monitoring and collection around rock piles, and water treatment where necessary (eg. special waste piles).

## TABLE 2.1

### Specific Surface Water Quality Objectives for the Protection of Aquatic Life and Wildlife

(values are in mg/L unless otherwise stated)

| Parameter | Concentration (mg/L unless otherwise stated) |
|---|---|
| Arsenic (total) | 0.05 |
| Barium (total) | 1.0 |
| Cadmium (total) | 0.001 |
| Chlorine (total | 0.002 |
| Chromium (total) | 0.020 |
| Copper (total) | 0.01 |
| Cyanide (total) | 0.01 |
| Iron (total) | 1.0 |
| Lead (total) | 0.02 |
| Mercury (total) | 0.0001 |
| Nickel (total) | 0.025 where hardness ≤ 100 mg/L ($CaCO_3$)<br>0.100 where hardness > 100 mg/L ($CaCO_3$) |
| Oxygen (dissolved) | 6.0 Protection of early life stage of warm water biota<br>5.0 - other life stages of warm water biota<br>9.5 - early life stages of cold water biota<br>6.5 - other life stages of cold water biota |
| Selenium (total) | 0.01 |
| Silver (total) | 0.01 |
| Temperature | not to be altered by more than 3° C from ambient water |
| Zinc (total) | 0.05 |
| Ra 226* | 0.11 Bq/L |

*General Surface Water Quality Objectives

The extent to which acid generation enhanced leaching is affecting drainage water quality is difficult to assess, as the available data are limited. The available data for active mines were summarized by MPCB (1990) for gold and uranium properties in northern Saskatchewan. A review of these data indicated a lack of a consistent approach to assessing mine rock piles and inconsistencies in collecting data from site to site. The need for a coherent approach to site assessment and development of rock pile water quality control was demonstrated.

In general, the review found that:

- There are two principle mechanisms of contaminant release at these sites:
  - flushing and leaching of readily soluble metals such as arsenic, nickel and radionuclides; and,
  - oxidation and generation of acidic drainage containing elevated metal levels.
- Arsenic, nickel, and radionuclides were the primary contaminants of concern even at early stages of operation and were evident in the drainage from several sites. Monitoring for other metals is relatively limited.
- Metal release was not directly proportional to "ore" and "waste" cutoff grades. These cutoff values are based on economic uranium cut-off grade, and are not specifically related to other metal enrichment grades.
- There is limited information available with respect to prediction of acid generation potential and actual field behaviour, although it appears that mine rock that is classified as "non-acid generating" can still be a significant source of contaminants.
- Testing for leaching and acid generation potential has not been standardized and therefore it is difficult to compare results and build a comparative database.
- Procedures that have been used are not necessarily the appropriate methods for the objectives, and do not represent natural conditions. For example, prediction of acid generation potential from an on-land rock dump cannot be made from a saturated kinetic test (which would actually simulate a saturated disposal or water cover option).

### 2.3.2 General Geology

The major uranium producers in Saskatchewan lie within or adjacent to the Athabasca Basin as shown in Figure 2.1. The basin is a very large, roughly circular structure occupying about

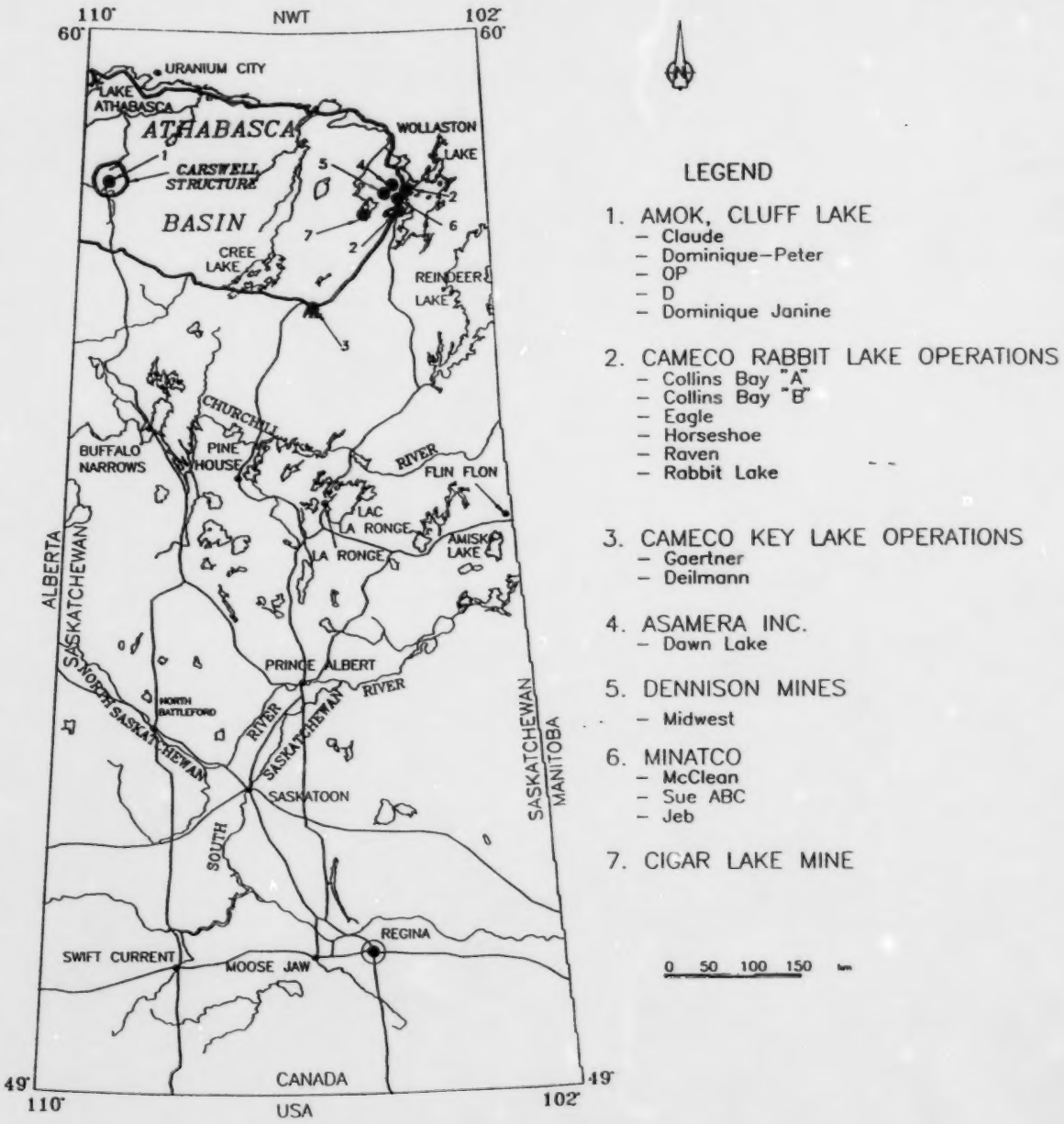



Figure 2.1 Uranium Deposits of Northern Saskatchewan

100,000 km$^2$ of northwestern Saskatchewan, extending approximately 50 km into Alberta.

The basin is filled with a thick sequence of generally flat lying Helikian aged (1.4 to 1.2 billion years) sediments, sandstones and conglomerates (Athabasca Formation) resting unconformably on top of a crystalline basement.

The basement consists of metamorphosed, deformed and recrystallized sedimentary rocks of Aphebean age (2.0 to 1.5 billion years). Basement rocks are typical Canadian Shield schist and gneiss with granitic intrusive complexes. During the Hudsonian Orogeny, roughly 1.8 billion years ago, the basement rocks were metamorphosed and remobilized to varying degrees (Langford, 1986).

The Carswell structure, a circular crater situated in the Athabasca Basin (Laine, 1986), is believed to have been formed by a sudden explosion from a meteor impact or volcanic activity approximately 480 million years ago. The structure consists of a 20 km diameter metamorphosed gneissic core surrounded by the Athabasca Formation.

The distribution of known deposits, which occur mainly along the margin of the basin and within the Carswell Structure, is controlled by the structural and lithological features of both the crystalline basement and sedimentary cover (Trembley, 1978, Laine, 1986). Many of the deposits are adjacent or close to the major unconformity separating the Athabasca Formation from the basement rocks.

There are 2 main types of deposits;

- basement hosted;
- sediment hosted deposits (also known as unconformity type).

Basement hosted deposits occur within or are very close to faults, shears and mylonite zones within the schists and gneisses of the basement rocks. Examples include the Dominique-Peter, Claude and parts of the Cluff Lake deposits (Laine, 1986). Sediment hosted deposits occur within the sandstones and conglomerates of the Athabasca Basin or their older metamorphic equivalents, in close proximity or adjacent to the unconformity. They are believed to be formed

from the remobilization of the minerals present in the basement (Ward, 1989). Examples include the Dawn Lake, Key Lake, Midwest, and Rabbit Lake deposits and parts of the Cluff Lake deposits. Since both types occur adjacent to the Aphebian-Helikian unconformity it is common to see deposits that exhibit basement and sediment hosted features, for example the McClean uranium deposits (Wallis et al, 1986). The mine sites are shown in Figure 2.1.

*Mineralization*

In general the basement hosted deposits tend to be polymetallic while the sediment hosted deposits are essentially monomineralic (i.e. have noticeably fewer mineral assemblages than the basement hosted deposits).

The sediment hosted deposits are formed from the remobilization of the uranium mineralization present in the basement rocks (Ward, 1989) during three distinct episodes (Laine, 1986; Ruzicka, 1986; deCarle, 1986):

- 1300 to 1050 Ma
- 850 Ma
- 380 to 200 Ma

The main mineralizing event affecting both the basement rocks and sandstone covers occurred from 1300 to 1050 Ma (Laine, 1986). Mineralizing solutions were structurally controlled by mylonite zones. Mineralization consists of uraninite, bravoite, coffinite, selenides, copper, lead, zinc, nickel sulphides and arsenides, often native gold, silver and bismuth. Mineralized zones are often associated with phyllitic gangue. The second event (850 Ma) was mineralogy very similar to the first phase except for the noticeable lack of significant amounts of selenides and arsenides. The third phase of mineralization (380 to 200 Ma) is believed to be a remobilization of the previous mineralization with subsequent deposition into the overlying Athabasca Formation. Mineralogy consists mainly of pitchblende, uraninite, coffinite and hematite. Minor amounts of copper, lead, zinc, sulphides and native gold may be present. Carbonates may be present.

*Basement Hosted Deposits*

These are polymetallic vein type deposits occurring within faults, shears and mylonite zones in the basement rocks. The deposits contain a wide variety of uranium minerals and complexes, copper, lead, zinc, molybdenum, nickel, iron, and silver arsenides, selenides, sulphides, and tellurides. Native gold and bismuth may be present. The dominant uranium minerals include uraninite, bravoite, coffinite with lesser amounts of pitchblende. They occur as veinlets, pods, and lenses in the shear zones. Varying amounts from trace to several percent of pyrite, chalcopyrite, sphalerite, niccolite, rammelsbergite, gersdorffite, cobaltite, covelite, jordisite and so forth may be present. The composition and nature of the mineral assemblages are governed to a large degree by the composition of the basement rocks (Laine, 1986; Ey, 1985). The uranium grades vary from 0.1 % to several percent with the highest grade uranium deposits belonging to this class of deposit. In the Carswell Structure, bitumen is known to occur (Laine, 1986) although it is not reported in the other deposits in the basin. Faults, shears and mylonite zones control the placement of the mineralizing solutions (Wallis, et al, 1986, deCarle, 1986 and Laine, 1986). Age of the mineralization ranges from roughly 1300 to about 850 million years and reflects 2 mineralizing episodes (Laine, 1986).

*Sediment Hosted Deposits*

These deposits are generally considered to be monomineralic in nature. The mineralogy is generally simpler and there are fewer uranium minerals, copper, lead, zinc, molybdenum, nickel, selenium and iron sulphides and arsenides. Native gold may be present. The dominant uranium minerals include pitchblende and coffinite with minor amounts of very complex uranium minerals. They tend to occur as coatings, disseminations, fracture coatings and massive concentrations. Hematite is present. There are generally minor amounts of pyrite, chalcopyrite, sphalerite, niccolite, covelite, marcasite, clausthalite, millerite and so forth present; although local concentrations can exceed several percent. Uranium grades vary from 0.1 % to several percent. Faulting may be present. Age of mineralization varies from roughly 850 to 350 million years and can reflect several episodes (Laine, 1986).

*Alteration*

Clay alteration occurs in all deposits. It is intense within the mineralized zones where the ore minerals are often surrounded by clay envelopes. Chlorite, illite, sericite, and argillite are the dominant clay minerals. Kaolinite is often present as are calcite and dolomite. Hematization can be seen around the mineralized zones.

# 3.0 ACID GENERATION AND METAL LEACHING

## 3.1 Introduction - The Generation of Contaminated Drainage

Contaminated drainage in this document refers to drainage water which contains levels of any element or contaminant which is not in compliance with regulatory limits for water draining from a site, or would cause adverse environmental impact. This would generally include, but may not be limited to, the following:

- pH, acidity, alkalinity;
- sulphate;
- nutrients;
- metals (dissolved or total);
- radioactive nuclides;
- total dissolved solids (TDS); and,
- total suspended solids (TSS).

There are two primary mechanisms for the generation of contaminated drainage from mine rock:

- flushing and leaching of readily soluble metals and contaminants under neutral or close to neutral pH conditions; and,
- chemical oxidation and acid generation resulting in the release of metals and contaminants and subsequent leaching under acidic conditions.

The difference in the geochemistry and the rate and source of contaminant production from each of these mechanisms must be recognized both for prediction of drainage water quality and development of control technology. Figure 3.1 schematically represents the flushing of contaminants from mine rock over time. The diagram can be equally applicable to laboratory prediction testing or field water quality, and demonstrates the key difference between the rapid early release of readily soluble contaminants and slower release of products by acid generation.

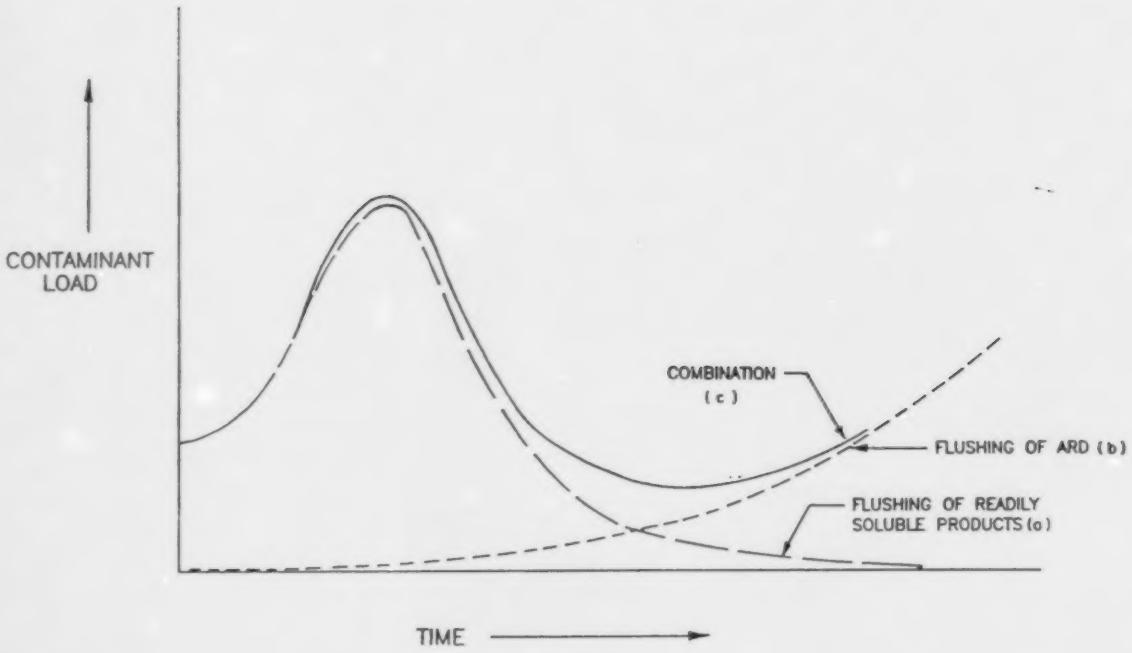



Figure 3.1 Flushing of Contaminants from Mine Rock with Time

The dashed line (a) represents metal leaching with an initial peak of loading, followed by a decreasing load as the products along the drainage flowpaths are flushed. In a laboratory test, the peak may be in the early flushing cycles, perhaps from 2 to 5 pore volumes, although this depends on the soluble load. Drainage water quality must be analyzed (particularly sulphate, acidity and pH in addition to metals) during this period, as there may also be some release of stored oxidation products. The contaminant load peak in the field may last for several weeks to years, depending on the climate, infiltration, flushing regime and soluble product load.

The dashed line (b) represents the release of ARD. The oxidation processes develop over time, and the lag to acid production may be weeks or years, depending on the neutralizing potential of a sample. The solid line represents what is probably a "typical" water quality load for many sites with both leaching and ARD. In the early stages there is a flush of contaminants from the more readily soluble constituents. The drainage would probably be near neutral with elevated arsenic, nickel and radionuclides. Over time this load may decrease and, as oxidation increases, sulphate, iron and acidity would increase. A second contaminant loading peak would be evident as metals are released through oxidation and acidic leaching.

The quality of water draining from rock piles will be controlled by the physical and geochemical nature of the rock pile and/or the site. The chemical and physical conditions and controls on acid generation that exist within a mine rock pile are extremely heterogeneous and anisotropic, at both a micro and macro scale, as illustrated in Figure 3.2.

These conditions vary in time with the rate and extent of acid generation, drainage processes, and also spatially with the nature of the mine rock material. Thus local seeps of quite different water quality can issue from the same rock pile. The solution chemistry of the resulting drainage from the rock pile is therefore dependent on the reactions and drainage from any number of local environments within the pile. Testwork is required for prediction of water quality, to address the heterogeneity of the mine rock and the variability of site conditions.

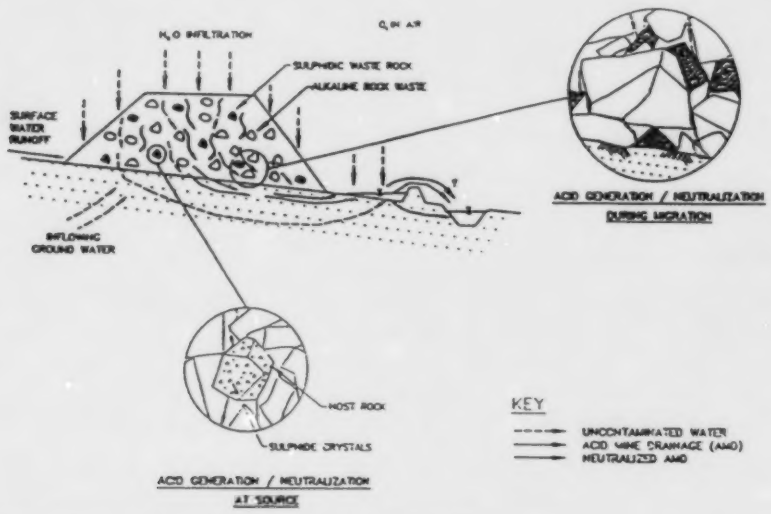



Figure 3.2 Generation of ARD from Mine Rock Dumps

With respect to acidic rock drainage, the primary concerns would be elevated acidity, sulphate, and the leaching of metals associated with the sulphidic ore, typically copper, nickel, arsenic, zinc and iron. In many rock types found in the uranium mining areas there are readily soluble (in varying degrees) contaminants associated with the host rock or ore grade material, notably arsenic, nickel and uranium, and to a lesser extent, copper, zinc and cadmium.

There are several factors that control drainage water quality:

- rate and extent of acid generation;
- rate and extent of metal release;
- hydrological regime of the rock pile including storage within the rock pile due to evaporation, transportation from the pile due to flushing, and development of specific flow paths; and,
- hydrological regime of the site considering patterns of precipitation and evaporation, high and low flow periods, spring freshet, and the nature of the receiving environment.

Each of these controls will be discussed in the following chapters to summarize the key processes, the assessment or prediction of the relative influence of each of these processes for a site, the available control technology, and the approach to selecting the most appropriate controls for drainage water quality protection.

## 3.2 Acid Generation

### 3.2.1 Introduction

Acid generation is caused by the oxidation of sulphide minerals when exposed to air and water, resulting in the production of acidity, sulphate and the release of metals. This is a result of the oxidation of sulphur in the mineral to a higher oxidation state. Not all sulphide minerals are equally reactive nor is acidity produced equally. Also, not all sulphidic minerals or sulphide bearing rock are potentially acid generating. The ability of a particular rock sample to generate net acidity is a function of the relative content of acid generating minerals and acid consuming minerals.

The factors that control the rate and extent of the acid generation, and the resultant drainage water quality have been studied in detail only in the last twenty years. It is now recognized that certain conditions, such as the correct combination of mineralogy, water, and oxygen, are necessary for the development of acidic rock drainage.

Sulphide minerals are ubiquitous in the geological environment, but are primarily found in rock that lies beneath a mantle of soil and often beneath the water table. Under natural conditions, the overlying soil and groundwater minimize contact with oxygen and thus allow acid generation to proceed at such a low rate that the effect on background water quality is negligible or not detectable. The exposure of reactive sulphidic rock to air and water, as a result of activities such as road building or mining, may accelerate the rate of acid generation and cause an impact on the environment.

The capability of a particular rock sample to generate net acidity is a function of the balance between the potentially acid producing (sulphide) minerals and the potentially acid consuming (alkaline) minerals. This balance is commanded by the physical and chemical controls on

the relative rate of acid generation and acid consumption. The process by which acid is consumed is known as "neutralization". Acidic waters generated by sulphide oxidation in a rock may be neutralized upon contact with acid-consuming minerals. As a result, the water draining from the rock may have a neutral pH and negligible acidity despite on-going sulphide oxidation. However, if the acid consuming minerals are dissolved, washed out, or coated by other minerals through encapsulation as a result of secondary mineralization, then, as acid generation continues, acidic water may eventually drain from the rock mass. Whenever the acid consuming capability of a rock (the "neutralization potential") exceeds acid generation capability, it is generally considered that any acid will be consumed and water draining from the rock will be at or close to neutral pH. There are limitations to this assumption as discussed in Chapter 3.2.4 and Chapter 5.6.

### 3.2.2 Reaction Chemistry

Acid generation and acid consumption are the result of a number of complex and interrelated chemical reactions. An understanding of the chemical processes and the reactants is key to predicting the potential for acid generation from a rock sample, and in identifying appropriate technology to prevent or control the generation of acidic drainage.

The primary components for acid generation are:

- reactive sulphide minerals;
- water or a humid atmosphere; and,
- an oxidant, particularly oxygen from the atmosphere or from chemical sources.

Acid generation reactions are generally expressed for the oxidation of pyrite; one of the most common sulphide minerals. The overall acid generation reaction showing pyrite oxidized by oxygen can be represented by:

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (3.1)$$

The dissolved iron and sulphate represents an increase in the total dissolved solids, and the $H^+$ a decrease in the pH if not neutralized. Should the environment be sufficiently oxidizing, the ferrous iron may be oxidized to the ferric state as follows:

$$2Fe^{2+} + \frac{1}{2} O_2 \longleftrightarrow 2Fe^{3+} + H_2O \quad (3.2)$$

The ferric in turn serves as an oxidant and may promote the chemical oxidation of sulphide minerals. In the case of pyrite, the reaction proceeds as follows:

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 16H^+ + 2SO_4^{2-} \quad (3.3)$$

The overall oxidation of pyrite and the regeneration of the ferrous iron to the ferric state is illustrated in Figure 3.3. Certain bacteria may accelerate the rate at which some of the above reactions proceed, thereby increasing the rate of acid generation. *Thiobacillus ferrooxidans* is capable of oxidizing reduced sulphur compounds, as well as ferrous iron to the ferric iron state. Other bacterial species known to participate or accelerate the oxidation of sulphide minerals include *Thiobacillus thiooxidans* and *Sulfolobus*. These species derive their energy for cell reproduction from the chemical reaction energy released during the oxidation process. Amongst others, the rate of bacterial cell growth and thus the rate at which bacterial oxidation proceeds is dependent on the following parameters:

- temperature;
- pH;
- availability of oxygen;
- availability of carbon dioxide (carbon source for cell reproduction);
- nutrients (N,P); and,
- surface area of exposed sulphide mineral.

The effects of temperature and pH on the biological and chemical oxidation of pyrite are illustrated in Figures 3.4 and 3.5 respectively.

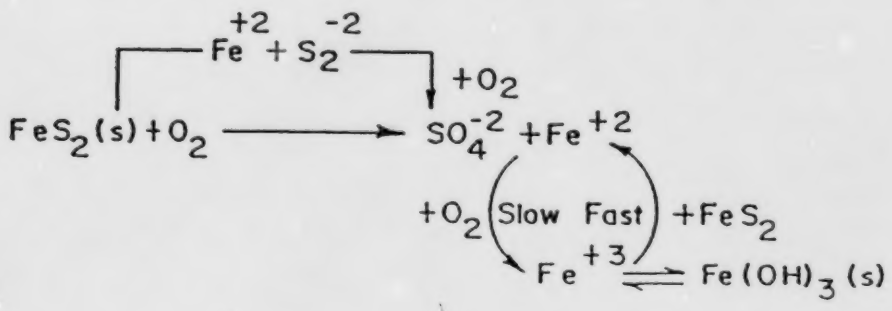



Figure 3.3 Overall Process (Stumm and Morgan, 1981)

### 3.2.3 Neutralization

Following the oxidation of a sulphide mineral, the resulting acid products may either be immediately flushed away by water moving over the rock or, if there is no water movement, accumulate in the rock while remaining readily available for flushing. If the acid products are flushed away from the sulphide mineral, they may eventually encounter an acid consuming mineral; the resulting neutralization will remove a portion of the acidity and iron from solution and will neutralize pH. Sulphate concentrations will usually not be affected by neutralization unless mineral saturation with respect to gypsum is attained. Consequently, sulphate may sometimes be used as an overall indicator of the extent of acid generation even after neutralization by acid consuming minerals has occurred.

The most common acid consuming mineral is calcite ($CaCO_3$), which consume acidity through the creation of $HCO_3^-$ or $H_2CO_3^0$:

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \quad (3.4)$$

and

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2CO_3^0 \quad (3.5)$$

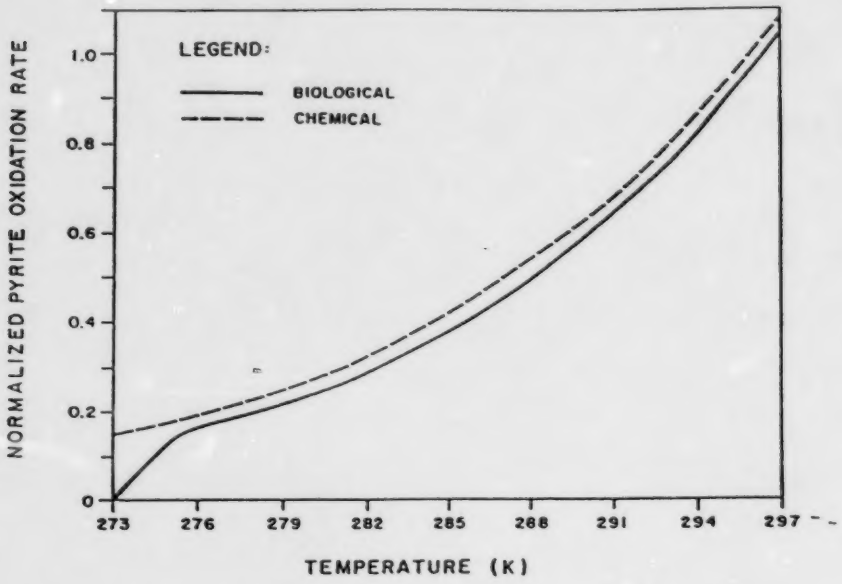



Figure 3.4 Effect of Temperature on Biological and Chemical Oxidation Rate

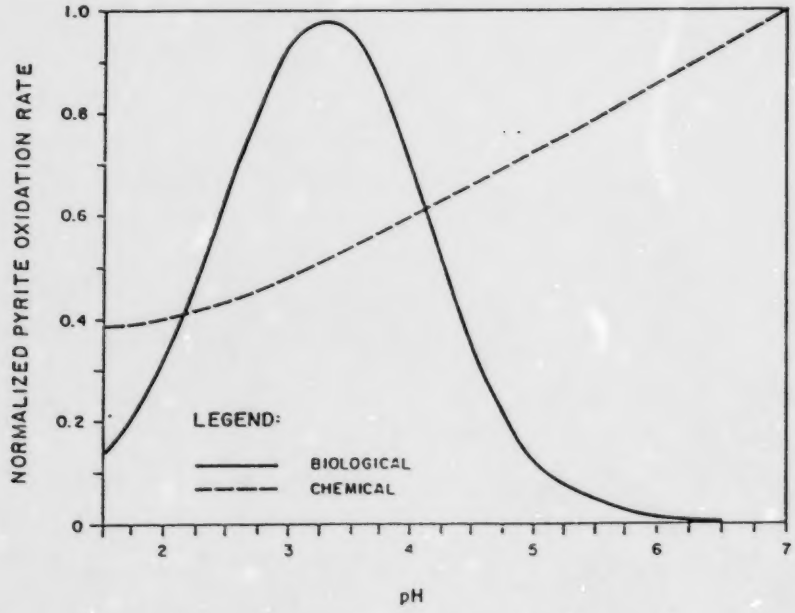



Figure 3.5 Effect on pH on Biological and Chemical Oxidation Rate

There are also other acid consuming minerals such as $Al(OH_3)$ (Table 3.1):

$$Al(OH)_3 + 3H^+ \text{ --> } Al^{3+} + 3H_2O \quad (3.6)$$

It is not unusual for a rock to contain both sulphide minerals and acid consuming minerals. The balance between the two types will determine whether the rock will eventually produce acid conditions in the water passing over and through the rock, and this balance forms the basis of the experimental procedure used in static tests (Chapter 5.6).

### 3.2.4 Stages in the Development of ARD

The development of acid rock drainage is a staged process involving both chemical and physical oxidation reactions. It is generally viewed as a three stage process defined by the pH of the water in the micro-environment of the sulphide minerals, as shown in Figure 3.6.

**Stage 1** As the rock containing sulphide minerals is initially exposed to oxygen and water in the early stages of oxidation, the pH is nearly neutral. As shown in the Stage I reactions on Figure 3.5, this is the period of primarily chemical oxidation. Oxygen is the primary oxidant, producing sulphate and acidity from the oxidation of the sulphide minerals. Any calcium-based carbonate such as calcite ($CaCO_3$) in the rock neutralizes this small amount of acidity and maintains neutral to alkaline (pH >7) in the water passing over the rock. Ferrous iron is released into solution. Since chemical oxidation of ferrous iron is very rapid above pH 7, and ferric iron is precipitated from solution as a hydroxide, the rate of pyrite oxidation is controlled at a low rate by the loss of ferric iron from solution.

Drainage water at this stage is generally characterized by the buffering capacity of the waste and the rate of flushing. Typically runoff contains high sulphate levels with a neutral or close to neutral pH. The acid produced is buffered while the ferric is precipitated as the hydroxide.

**Stage II** As acid generation continues and the calcium-based carbonate is consumed or becomes unavailable, the pH of the water decreases, and the process moves towards the second stage. With pH in the micro-environment decreasing towards pH 4.5, both chemical and biological oxidation reactions occur.

## TABLE 3.1

### Summary of Acid Consuming Minerals and Their Neutralizing Characteristics

| Mineral | Composition | Acid[1] Consuming Potential | Buffer pH |
|---|---|---|---|
| Calcite, Aragonite | $CaCO_3$ | 100 | 5.5 - 6.9 |
| Siderite | $FeCO_3$ | 116 | 5.1 - 6.0 |
| Magne site | $MgCO_3$ | 84 | |
| Rhodochrosite | $MnCo_3$ | 115 | |
| Witherite | $BaCO_3$ | 196 | |
| Ankerite | $CaFe(CO_3)_2$ | 108 | |
| Dolomite | $MgCa(CO_3)_2$ | 92 | |
| Malachite | $Cu_2CO_3(OH)_2$ | 74 | 5.1 - 6.0 |
| Gibbsite | $Al(OH)_3$ | 26 | 4.3 - 3.7 |
| Limonite/Geothite | FeOOH | 89 | 3.0 - 3.7 |
| Manganite | MnOOH | 88 | |
| Brucite | $Mg(OH)_2$ | 29 | |

Notes

1 Acid consuming potential is given as the weight (g) of the mineral required to have the same neutralizing effect as 100 g of calcite. For example, the mole weight of siderite is 116 g and the mole weight of calcite is 100 g. Therefore, 116 g of siderite are required to supply the same amount of alkalinity as 100 g of calcite although the two minerals will not necessarily neutralize low pH waters to the same pH (see buffer pH column).

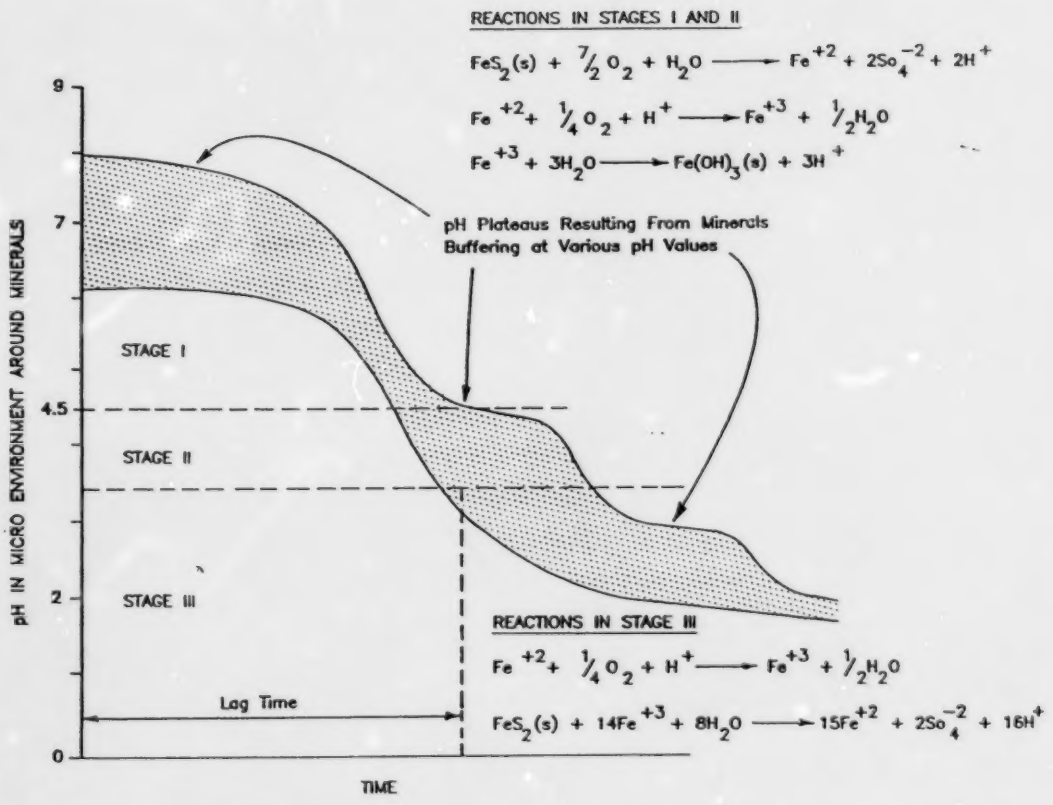

REACTIONS IN STAGES I AND II
$FeS_2(s) + {}^{7}/_{2}O_2 + H_2O \longrightarrow Fe^{+2} + 2So_4^{-2} + 2H^+$
$Fe^{+2} + {}^{1}/_{4}O_2 + H^+ \longrightarrow Fe^{+3} + {}^{1}/_{2}H_2O$
$Fe^{+3} + 3H_2O \longrightarrow Fe(OH)_3(s) + 3H^+$
pH Plateaus Resulting From Minerals Buffering at Various pH Values
pH IN MICRO ENVIRONMENT AROUND MINERALS
9
7
4.5
2
0
STAGE I
STAGE II
STAGE III
Lag Time
TIME
REACTIONS IN STAGE III
$Fe^{+2} + {}^{1}/_{4}O_2 + H^+ \longrightarrow Fe^{+3} + {}^{1}/_{2}H_2O$
$FeS_2(s) + 14Fe^{+3} + 8H_2O \longrightarrow 15Fe^{+2} + 2So_4^{-2} + 16H^+$

Figure 3.6 Stages in the Formation of Acid Mine Drainage

As the rate of acid generation accelerates in Stages II and III, the pH progressively decreases in a theoretical step-like manner as shown in Figure 3.6. Each plateau of relatively steady pH represents the dissolution of a neutralizing mineral that becomes soluble at that pH. If the oxidation continues until all the neutralization potential is removed, then pH values below 4.5 will occur.

The drainage water for this stage is generally close to neutral, while elevated ferrous iron and sulphate concentrations are observed. A relatively high acidity is observed even though the metals in solution concentrations may be low.

**Stage III** As the alkali minerals are consumed or become unavailable, or acidity is produced at a faster rate than alkalinity, the pH becomes acidic and the dominating reactions change from chemical to primarily biologically catalyzed oxidation. Ferrous iron is produced from the sulphide oxidation reactions, and biologically oxidized to ferric iron, which in turn replaces oxygen as the primary oxidant. The rate of oxidation in this stage is considerable more rapid than in Stage I. As shown in Figure 3.5, decreasing pH enhances the rate of oxidation. The rates of biologically catalysed oxidation can be from fifty to one million times greater than those for chemical oxidation.

The drainage water at this stage is generally acidic and is characterized by elevated sulphate and metals in solution concentrations. Iron in solution occurs primarily as ferric iron ($Fe^{3+}$).

At some time in the future, decades and possibly centuries from the initiation of acid generation, the rate will slow as the more reactive sulphide has completely oxidized and pH will increase until the rock becomes essentially inert and the ambient pH of the water is not affected. The time scale for each successive stage may vary from a matter of days to a period of hundreds of years and is dependant on the factors controlling acid generation.

The stage in the oxidation process will determine the appropriate control technology. In Stage I, control of the conditions necessary for acid generation reactions may be feasible. Preventing contaminated drainage impacting on the environment may be achieved through the effective control of the oxidation process by the exclusion of the primary reactant necessary for the reaction to proceed (i.e. oxygen).

Once the acid generation reactions are established (Stages II and III), ferric iron becomes the dominant oxidant, and is regenerated by rapid biological oxidation. In this stage the surface of mine rock particles are coated with water containing acidic products and possibly evaporative deposits of acidic products. To prevent contaminated drainage requires the elimination of the transportation mechanism to prevent contaminant release to the environment.

## 3.3 Metal Leaching

The mineralogical nature and chemical environment of rock will determine the geochemical behaviour of different rock types. The solubility of various metals contained in the minerals in the rock is dependant on the form in which they occur (mineral) in the rock. The solubility of many metal forms increase with decrease in pH below neutral (pH=7). For such metals the solubility increases with each decreasing step in pH plateaus illustrated in Figure 3.6. Conversely, as pH increases along a flow path (due to plateau increases in the pH) some of the metals in solution may precipitate. In some instances, contaminated drainage will also serve as a leachant (lixiviant), promoting the solubilization of oxide minerals that may generally be inert or show low solubilities. For example, the generation of ferric iron may serve to oxidize certain uranium minerals, thus increasing the uranium solubility and leach rate.

The geological formations of the uranium rich orebodies in Saskatchewan have resulted in a number of characteristic features with respect to mineralization. As described in Section 2.1, the uranium minerals are generally associated with arsenic and nickel enrichments, and to a lesser degree, copper, zinc, cadmium and lead minerals. In Figure 3.7, the solubility of these minerals is shown as a function of pH.

In the case of the older or First and Second Phases of mineralization, these metals occur primarily as sulphides, which include chalcopyrite, pyrite, arsenopyrite and niccolite. Since the sulphide minerals of these metals tend to be highly insoluble at neutral pH conditions, mobilization will require oxidizing and depressed pH conditions. Once mobilised, some of these metals may be redeposited as metal hydroxides at neutral pH conditions, should pH increase. Under maintained acidic oxidizing conditions high leach rates resulting in elevated

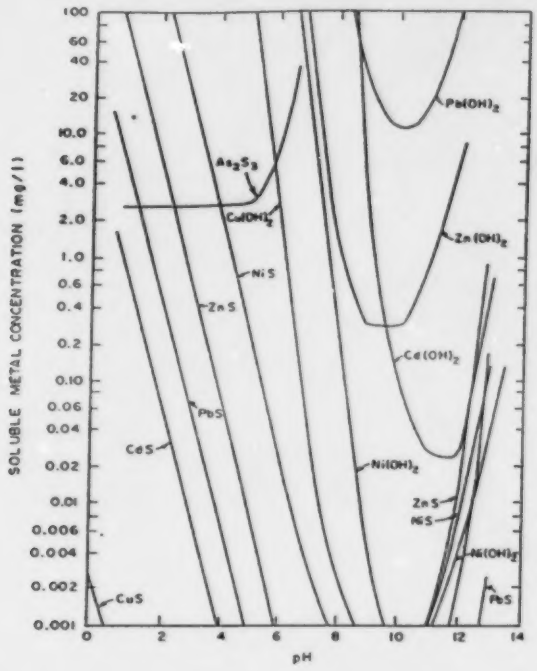



Figure 3.7 Calculated Metal Sulphide and Hydroxide Solubilities (Bhattacharrya et al., 1981)

concentrations of metals in solution are expected. The primary uranium minerals are uraninite, coffinite and brannenite. Generation of ferric iron as an oxidant will result in the mobilisation of uranium.

In the more recent mineralization or Third Phase, metals associated with the uranium minerals tend to occur in a more oxidized state, with some metals occurring as the sulpho-salts. Therefore, under neutral pH conditions, the solubility of these metals will be dictated by the solubility of the metal oxides and hydroxides. For example, the hydroxides of both arsenic and nickel are relatively soluble at a pH of 7, thus elevated solution concentrations can be expected. Copper hydroxide on the other hand is relatively insoluble at a neutral pH.

Some typical drainage qualities observed for rockpiles in Saskatchewan are illustrated in Table 3.2. The table shows both neutral and acidic drainage qualities occurring at different times of the year. It is important to note the elevated nickel and uranium concentrations may

**TABLE 3.2**

**Some Examples of Contaminated Runoff Water Quality Observed at Uranium Mine Rock Piles in Saskatchewan**

| PARAMETER | UNIT | EARLY JUNE | MID JUNE | EARLY AUGUST | MID AUGUST |
|---|---|---|---|---|---|
| Total Alkalinity | (mg/L) | 7 | NIL | 2 | NIL |
| Total Hardness | (mg/L) | 640 | 659 | 571 | 2190 |
| As | (µg/L) | 28 | 16 | <0.5 | 1120 |
| Cu | (mg/L) | 0.077 | 0.13 | 0.24 | 3.5 |
| Fe | (mg/L) | <0.001 | 0.50 | 0.025 | 70 |
| Ni | (mg/L) | 1.8 | 9.1 | 1.5 | 16 |
| Pb | (mg/L) | <0.005 | <0.005 | <0.005 | 0.16 |
| Zn | (mg/L) | 0.040 | 0.35 | 0.17 | 1.9 |
| TSS | (mg/L) | 55 | 40 | 5 | 27 |
| Cond- field | (µmho/cm) | 1170 | 1300 | 1150 | 4200 |
| - lab | (µmho/cm) | 1250 | 1370 | 1140 | 4790 |
| pH- field | (pH units) | 6.1 | 4.0 | 5.0 | 3.0 |
| - lab | (pH units) | 6.39 | 4.17 | 5.17 | 2.97 |
| Turbidity | (NTU) | 62 | 26 | 3.0 | 14 |
| Ra 226, Tot | (Bq/L) | 1.4 | 1.5 | 0.70 | 0.90 |
| U, Tot | (µg/L) | 72 | 10400 | 2950 | 14000 |

occur at a neutral pH. Acidic conditions generally result in a significant increase of metals in solution.

*Summary*

The quality of drainage water from Saskatchewan mine rock piles is dependant both on the presence of metals/minerals within the rock which are leachable at neutral pH (notably As, Ni and U) and on the increased leachability resulting from acid generation that can occur in some Saskatchewan uranium mine rock wastes where reactive sulphides are present in sufficient quantities.

Acid generation is controlled by:

- type of sulphide mineral;
- distribution and exposure of sulphide mineral;
- type, distribution and exposure of the alkaline minerals;
- chemical and biological oxidation characteristics;
- temperature and pH;
- oxygen and water flux; and,
- chemical concentrations.

Factors which control the rate and extent of acid generation are those which also provide potential for control of drainage water quality.

The development of ARD is a three stage process. Initially, relative slow chemical oxidation processes dominate and available alkalinity controls the pH values in the near neutral range. During this stage the acid products and leaching rate of many of the potential contaminants are reduced. As the available alkalinity is consumed, the pH becomes more acidic and the rate of oxidation increases. At pH values below 4.5 the more rapid biologically catalysed oxidation reactions predominate, pH decreases and the concentration of many contaminants increase.

Control of acid generation reactions in the early stages of oxidation requires either control of pH, to prevent the onset of biological oxidation, or control of the supply of oxygen, the primary oxidation. In the latter stages of rapid oxidation, control of the acid generation reactions is more difficult. Oxidation of sulphidic minerals produces ferrous iron. Biological activity oxidizes the ferrous to ferric iron, which then acts as the primary oxidant. In this stage of rapid oxidation the control of acid drainage must depend primarily on the prevention of acid product migration.

# 4.0 SITE ASSESSMENT

## 4.1 Introduction

Prediction of the development of the acid generation processes and resultant drainage quality is essential to the evaluation of the potential environmental impact of the rock piles and alternative abatement and closure procedures. It is required, from the early stages of operation, to identify mine rock that may result in a water quality problem, and develop control measures that can be implemented during mining.

The assessment and prediction of drainage water quality from mine rock piles is therefore a key component of the assessment of environmental impact from a mine site. Prior to approval of a new mine plan, or to changes or closure of an existing mine, assurance will be required that all potential sources of contaminated drainage have been identified, and that prevention or control measures have been incorporated into the mine plans where appropriate. As the understanding of long term environmental liabilities has developed, it has become increasingly apparent that this assessment is particularly important for operating mines which are preparing for closure. On closure, the final and adequate rehabilitation measures must be implemented. The opportunity for the cost effective implementation of further remediation measures as well as the ability to fund such activities from the mined resource usually ends with mine closure.

Prediction of drainage water quality for new mining operations, or further development of existing operations is based on information and sampling from the, as yet, unmined orebody drilling programs and bulk sampling. Such information is not always readily available for existing rock piles on mines which are currently in operation. Operating mines, in addition to examining old exploration records and core, may have to investigate and sample existing piles to assess current and long term drainage water quality in order to complete the design of closure measures.

For many operating mines the potential for contaminant leaching was not recognized during mine development. The techniques for prediction of ARD have really only developed and become widely applied in the past five years. Thus, for many mines the potential for acid generation and contaminant release was not recognized during the initial development and mines must now

assess drainage water quality from mine rock distributed throughout the site. The same prediction tests can be used as for new mine prediction, however site characterization, sampling and interpretation of results will be different, and perhaps more complex than for new mine prediction. Factors which complicate assessment and prediction for existing rock piles are in mine rock classification and sampling, and determining the distribution of the different classes.

This chapter discusses the techniques that can be used for site assessment of the potential for ARD and/or metal leaching from both new and operating mine sites and to establish the objectives and therefore the direction of any further prediction work.

## 4.2 Approach

Assessment and prediction of drainage water quality is based primarily on data which is rock type and site specific. There are a number of items that must be addressed for all sites. A general approach is outlined below:

1. Conduct an initial site assessment to answer the following questions: i) is there currently a drainage water quality problem, or is one likely to develop in the future? and ii) what is the level of concern based on the potential contaminants and the nature of the receiving water (ie. fisheries resource, drinking water source, dilution etc.)?

2. If the information is available, compare the site with nearby sites or natural water courses. This information is also important in identifying the level of concern with the site, and the water quality objectives.

3. Identify the types of mine rock and geological/lithological units by observation of fresh and stored drill core, core logs, wall rock exposures, mine plans and records, and solids assays.

4. Identify the geochemical nature of each unit including acid generation potential and potential soluble metals by static ARD prediction tests, leach tests, and mineralogy. Divide the lithological units into sub-units with potentially similar geochemical characteristics with respect to leaching and acid generation potential.

5. Identify quantities of each rock sub-unit type both in the ground and already extracted and stored in rock piles or distributed around the site (eg. for construction work). This will provide a preliminary indication of the areas requiring specific attention.

6. Based on the mine plan and mine rock management plan, determine the rate of production and period of exposure of mine rock to be placed in the piles; acid generating rock mined in early years, and which may be left exposed for long periods, must be identified.

7. Identify as accurately as possible the location of each class (or sub-unit) of mine rock within the piles from mine plan and schedule, pile construction sequence and method to determine the distribution of materials and, if necessary, appropriate sampling procedures (surface sampling, drilling, trenching) to further define mine rock type distribution in the piles.

8. Conduct laboratory and field test programs using static and kinetic procedures to determine ARD potential, rate of generation and change in quality of drainage water with time.

9. Extrapolate laboratory data for rates of oxidation and drainage water quality to field conditions and field time scale.

10. Apply hydrological data to predicted contaminant load production (typically a load produced per time and per unit mass or surface area of mine rock) from test program, and estimate drainage water quality for monthly averages, and peak conditions.

11. Assess environmental impact. If the impact is not acceptable it will be necessary to revise the mine rock management or closure plan and repeat the analyses in steps 6 through 11. Requirements for additional testing will be determined by changes to the management plan, and the information already available.

The stages in a site assessment are summarized in Table 4.1 highlighting the key areas that must be covered and indicating the chapters in which each aspect is discussed. The amount of time

## TABLE 4.1

### Stages in Site Assessment for Contaminated Drainage From Mine Rock Piles

| STAGE OF INVESTIGATION | ISSUES AND TASKS | REFERENCE | TIME PERIOD |
|---|---|---|---|
| Initial Assessment | · review of information<br>· comparisons with nearby sites and sites with equivalent geology/mineralogy<br>· site investigation and preliminary sampling of existing rock piles<br>· problem definition:<br>Is there currently a drainage water quality problem?<br>Might there be drainage water quality concerns in future?<br>What is the level of concern based on nature of drainage and receiving water? | Chap. 4 | 2 to 4 weeks |
| Establish Objectives of Assessment Program | · time period available for investigation?<br>· understanding of site<br>· requirement for immediate remediation<br>· design of closure options<br>· design or revision of current or proposed mine rock management plan | | 2 weeks |
| Detailed Site Investigation | · sampling and mine rock classification to identify homogeneous sub-units (classes) in terms of acid production or metal leaching potential;<br>· seep surveys | Chap. 5.5 | 1 week to several months |
| Sampling and Testing | · geochemical static testing on samples representative of each unit;<br>· geochemical kinetic testing on selected samples identified as potentially acid generating;<br>· leach extraction testing to determine readily soluble constituents;<br>· interpretation of results<br>· modelling to predict short and long term drainage water quality. | Chap. 5 | 3 to 12 months |
| Mine Rock Management Plan | · disposal options definition<br>· control options definition | Chap. 6 | 2 to 3 months |
| Environmental Impact Assessment | · baseline, background conditions definition<br>· predicted changes as a result of mine rock deposition both during operation and after closure | Chap. 7,8,9 | 3 months |

required to complete a reasonably detailed evaluation is also shown; however, the period may vary significantly with the complexity of the site, the amount of information readily available, and the extent to which detailed kinetic testing is required. Sources of data and information for both new mines, and existing or abandoned operations are indicated in Table 4.2.

## 4.3 Field Investigations

Field investigations are needed to evaluate specific problems or areas of concern at a mine site. They are used to detect early signs of ARD that may not be picked up by the compliance monitoring stations. Field investigations are particularly relevant to older mine sites, where there is little prediction testwork available, and the potential for ARD is not known. As discussed previously, acid generation prevention control measures are more desirable in the long term than collection and treatment of the drainage once it has started. It is critical to assess the potential for ARD or contaminated drainage collection at the earliest possible time to ensure that control measures can be effectively implemented. Once established, the effectiveness of a control technique must be evaluated through monitoring or further investigations.

Typically investigations are multistaged. An initial review of data from the site is carried out, and a one to two day site inspection is made. If the initial inspection indicates a potential problem, further investigations are warranted. Depending on the physical and chemical nature of the rock piles the investigation will vary.

### 4.3.1 Initial Investigation

One to two day site assessments are used to identify types and classes of mine rock, sources of contaminants, the nature of the problem, and to evaluate the need for, and determine the type of further investigations. It is critical that the investigation team walk the site and see the physical and geochemical conditions specific to the site. The approach may include the following:

- classification of mine rock by geology and mineralogy to give an indication of the sub-units or classes of mine rock expected on the site. Although the investigation may focus on the rock piles, a brief tour of the pit or underground mine geology is useful for identification of rock types and of how they look when freshly exposed;

## TABLE 4.2

### Sources of Information and Samples

| | NEW MINE | OPERATING MINE | ABANDONED MINE |
|---|---|---|---|
| Mine Rock Classification | · outcrop exposures<br>· exploration drill samples, logs<br>· exploration bulk sampling<br>· geological sections<br>· core assays | · outcrop and excavation exposures<br>· drill core<br>· production sampling<br>· core assays<br>· specific sampling from working areas and piles | · outcrop and excavations exposures<br>· drill core<br>· core assays<br>· specific sampling from piles |
| Mine Rock Distribution | · mine planning | · mine planning<br>· mine rock placement records<br>· pit and underground plans and exposures<br>· pile surveys<br>· pile drilling and sampling<br>· site personnel | · pit and underground exposures<br>· existing records and plans<br>· site personnel still available<br>· pile surveys<br>· pile drilling and sampling |
| Acid Generation, Leaching Potential | · static testing<br>· short term leach extractions<br>· mineralogy<br>· site comparisons | · observation of old core<br>· field sampling<br>· static testing of distinct sub-units from working areas<br>· static testing of pile samples<br>· site observations - venting, staining<br>· seep surveys | · observation of old core<br>· field sampling<br>· static testing of distinct units from working areas<br>· static testing of dump samples<br>· site observations - venting, staining<br>· seep surveys |
| Drainage Water Quality | · kinetic testing<br>· background water quality | · regular monitoring<br>· seep surveys<br>· kinetic testing<br>· leach extraction | · monitoring records<br>· seep survey<br>· kinetic testing<br>· leach extraction |

- review of water quality data to determine the types of contaminants leaching into water courses. A brief look at the water quality stations may indicate the need for more detailed sampling closer to the rock piles. It may be useful to collect a few water samples from the toe of the pile: pH and conductivity can be measured directly in the field;
- walking the site for indications of drainage water quality or ARD by visual observations, eg. staining, stored oxidation products etc. This investigation should begin by looking at the geological/lithological units at a workings face (open pit or underground) as identified by the geologists;
- samples from both the working areas and the rock dumps for paste pH measurements to indicate net acidity and alkalinity (and an indication of the presence of storage of readily soluble products) in rock piles. Paste pH measurements (Canmet-MEND, 1990) can be conducted by mixing 10 g of sample with 20 ml of water, gently agitating and measuring the pH of the slurry with a field pH instrument. Hydrochloric acid can be used to indicate the presence of neutralizing minerals by adding the acid (usually 10% v/v) and observing the resultant "fizz" in the presence of alkali minerals;
- field extraction testing: conductivity is measured to indicate the relative concentration of total dissolved solids in the leachate, indicating a storage of oxidation products such as sulphates and hydroxides produced during the breakdown of metal sulphides in the piles. The measurement is similar to paste pH in that a sample of solids is slurried with a known volume of distilled or deionized water and conductivity measured.
- water and solids sampling: collected if the initial investigation indicates a need for further laboratory testing.

For this type of investigation, relatively simple equipment is required. Water sampling equipment, pH paper or a pH meter, 10% hydrochloric acid solution, hand lens, rock hammer and a mineral identification guide and sample bags. Sulphate analysis can also be carried out in the field with some specialized equipment. The above mentioned field tests are simplified versions of standard laboratory procedures and are intended to provide a relative indication of the extent of soluble product storage and oxidation.

Surface pools, seeps at the toe of rock dumps, surface runoff, and groundwater monitoring wells around the rock dumps should all be examined for early signs of ARD. The best time for field investigations is during the spring freshet or during or immediately following heavy rains. Summer investigations are useful for detecting staining and precipitates along water courses. The first snowfall of the year may indicate "hot spots" in the dumps, indicating microbial activity and rapid oxidation within the dumps.

Increasing sulphate, acidity, and metals levels in seeps or decreasing pH and alkalinity relative to background conditions may indicate that metals leaching and/or acid generation is taking place. Observations of visibly oxidized pyrite or pyrrhotite, coloured precipitates or water, dead vegetation or an unhealthy ecosystem, and melting snow or steam vents on rock piles may indicate acid mine drainage. Sulphides in highly weathered or slaking rocks are more readily exposed to oxygen and water, and thus have a higher potential for rapid oxidation and for leachate flushing. Fine particulate material may wash out of the dumps and increase turbidity in the water or be transported by wind to surrounding areas.

The techniques described above are relatively simple techniques that can be applied at most sites to provide an initial assessment, indicate the potential rock classes of concern, and to develop a more detailed investigation program appropriate to the site. Such reconnaissance level investigations were conducted at three uranium mines in Saskatchewan prior to the preparation of these guidelines. The importance of an understanding of the site, the local geology, and of the processes involved in contaminant release and migration within a rock dump was summarized briefly in Chapter 3.

### 4.3.2 Seep Surveys

As discussed in Chapter 3, the quality of water draining from a pile is a combination of the seepage from different rock classes and flow paths within the pile. Frequently this mixing of water can mask seeps of specific interest: seeps that may be indications of the onset or the reduction of oxidation and/or leaching. For large rock piles that have been developed by progressive dumping, there may be specific areas which require control and other areas which do not.

Rock classification, pile records and seep surveys can be used to indicate the specific areas of concern. Isolated acidic seeps can be identified to give a better understanding of the site specific conditions pertinent to contaminant leaching or leading to acid generation. Often this type of analysis is used to isolate specific zones of a rock pile that could be remediated by the use of covers or water diversion.

The most useful sampling period is typically during the spring freshet when snow melt contributes to high flows and the greatest sediment and contaminant loads of the year. Depending on the needs of the program, quarterly or monthly sampling is conducted to give an indication of the seasonal variation in concentration and loading. For a proper evaluation, seep surveys should be conducted over a period of at least one and preferably two years. If the program is intended to monitor changes through time of a new mine rock pile sampling could be conducted once a year at spring freshet for the entire life of the mine.

### 4.3.3 Detailed Laboratory Studies

When the potential for ARD or metal leaching has been identified, the next step is to define the ultimate extent and find the most cost effective way of ameliorating the problem. In order to do this further testing may be required to evaluate the specific sources of contaminants, the rate of release, and factors which control metal release and migration. This is discussed in detail in Chapter 5. Control measures can also be tested on a laboratory scale to assess the applicability to the site and predict drainage water quality. Static and kinetic tests may be conducted to delineate the rock units contributing to the generation of acid. Additional monitoring may be required on the site. Detailed seep surveys are needed to delineate the problem areas. Rock piles may be instrumented to characterize the unique physical conditions found within.

### 4.3.4 Detailed Field Investigations

The extent to which acid generation has occurred within an existing pile, and prediction of the stored oxidation and readily leachable products is critical to evaluation of drainage water quality and the control technology. If the available information is limited there may be a

requirement to investigate the physical and geochemical nature of the pile. Drilling and instrumentation is often the only option available to evaluate water quality for an existing pile for which long term prediction is required, or for a pile undergoing remediation. Interpretation of the results requires a good appreciation of the limitations of such sampling. Considerations in a field program include:

- Test pitting or trenching are the preferred sampling forms since they provide a large in-situ exposure of rock for visual inspection. Representative samples can be collected from the excavation walls or floor. For large piles, samples cannot be obtained at depth and drilling may be required.

- Drill type. Particle size is a key factor is determining contaminant release and ARD potential. Contamination, removal of fines, and sample crushing must be considered in selecting the drill equipment. Samples from a Becker Hammer or air rotary drill are typically most suitable for kinetic testing.

- Purpose and therefore scope of drilling program. Samples collected from a pile drilling program will only be representative of the drill hole. It is difficult, without detailed pile development records and sample classification, to relate drill hole samples to distribution of mine rock throughout the pile. Therefore a drilling program should only be considered if either i) there are no other sources of appropriate samples, or ii) if instrumentation will be installed to investigate the physical and chemical regime within the pile.

- Time period. Monitoring of pile performance, either without or with ARD and leaching controls (eg. covers) requires several years to understand and evaluate trends and changes in data. This information is key to evaluating long term performance.

Investigation and monitoring of an existing dump may include:

- surface solids classification and sampling;
- hydrology, hydrogeology, and seepage definition;

- test-pitting and drilling for rock classification and sampling at depth;
- solids sampling for static testing and geochemical analysis;
- solids sampling for kinetic or leach extraction testing;
- installation of instrumentation:
  - lysimeters for water sample collection below cover or pile
  - piezometers for water table monitoring and water sampling
  - pore gas sampling - oxygen, carbon dioxide, radon
  - temperature probes
- drainage water collection and sampling;
- sampling for particle size distribution;
- seep surveys.

### 4.3.5 Rock Pile Instrumentation

Rock piles have a number of unique physical conditions that must be evaluated in the design and monitoring of control measures for drainage water quality. Understanding the dump specific factors may improve the effectiveness of a control option. Dumps may be drilled and instrumented with oxygen/carbon dioxide monitors, thermistors (to measure temperature), piezometers/water samplers and lysimeters (to locate the groundwater table, sample water and collect infiltration inside the dump). From this instrumentation the air and heat flow conditions within the dump can be evaluated. Once installed, the instrumented drillholes can be used to monitor evolution of acid generation and/or leaching as well as the effectiveness of control measures. During the drilling program sample mine rock can be classified and samples collected for further testing, to relate the material found in each drillhole to the estimated distribution of mine rock classes in the rock pile. An estimate of this distribution is required to predict short and long-term drainage water quality and evaluate requirements for control measures.

### 4.3.6 Sediment Sampling

Water quality can be directly influenced by sediment and sedimentation characteristics, because of the important role it plays in removal of metals and other contaminants from water

(Environment Canada, 1983). Sediments can also be a source of metal release, and are a potential route of ingestion for bottom dwelling and feeding organisms in the aquatic environment.

Sediment sampling programs related to runoff from mine waste rock are not typically part of a regular monitoring unless the mine rock is being deposited in a water body, or drainage water from the site carries a significant particulate load into the receiving waters. Specific, or periodic, sediment sampling is useful to determine baseline conditions in the receiving environment, the transport of particulates in drainage water, and the uptake or release of metals from sediments.

Sediment sampling includes: suspended sediments, and bottom sediments. It also can include above water surface samples in areas where there is periodic flooding or windborne dust. The suspended sediments load in drainage water can be measured by the total and dissolved metals, and total suspended solids. Bottom sediments are collected by use of coring or grab samplers, depending on the requirements of the program for sample integrity. Detailed descriptions of sampling methods are found in "Sampling for Water Quality" (Environment Canada, 1983). Samples are typically analyzed for total metals. Pore water samples may be collected for analysis in some cases, although specialized equipment for sampling and extraction is required. Pore water samples must be collected carefully to reflect in-situ conditions as the oxidation/reduction profile which exists over depth in the sediments will affect the pore water chemistry. Leach tests such as the TCLP or SWEP procedures (see Chapter 5.7) can also be conducted to evaluate the potential for remobilization of metals into the environment. Bacterial counts may be conducted where the presence of bacteria contributing to either metal uptake or release through oxidation, acid generation or sulphate metal reduction is suspected.

The location and number of sampling stations will depend on the configuration of the "source" or inflow to the receiving environment, and the receiving lake or river. All sampling programs must include upstream, or background samples for comparison. It is also important to recognize the potential for natural enrichment of the sediments as a result of natural erosion and transport of fines from mineralized rock.

The specific sampling program will depend on the site characteristics but as a general guide:

- sample along drainage flowpath;
- sample a transect across a river with sediment depth profiles appropriate to the material deposition pattern;
- sample around the outlet of a point source discharge;
- sample along the length of a non-point source (eg. Seepage along a river bank or lakeshore).

These sediment sampling programs should be conducted in accordance with standard practices, considering the regular overall site monitoring programs, and in consultation with regulatory authorities familiar with the site.

### 4.3.7 Biological Monitoring

Biological monitoring or *environmental effects monitoring* is a technique which is being proposed more frequently as a measure to evaluate the environmental impact of a discharge.

Such monitoring can be used as an indication of the health of the ecosystem affected by mining, and may be applicable in an environmentally sensitive area, with significant aquatic resources. However, biological sampling is more frequently used in targeted research programs addressing a specific concern with respect to an aquatic resource.

Biological monitoring may be applicable for evaluation of rock pile runoff on a site specific basis. However, the need for and design of any biological monitoring program should be developed by site personnel in conjunction with regulatory authorities familiar with site.

# 5.0 PREDICTION

## 5.1 Approach to Prediction

The prediction of the potential for acid generation and metal leaching is important from both an environmental and an economic perspective. The early identification of "problem" wastes and development of an appropriate waste management plan can significantly reduce long term environmental problems and remediation costs. Early identification and incorporation of control measures can also reduce the financial liabilities of maintaining long term collection and treatment facilities, such as a chemical treatment plant, in perpetuity. It is important to the mining company as well as to the regulatory authorities to do sufficient, appropriate testing to ensure that all potential problems have been identified and addressed.

Prediction testing should be conducted throughout the mine life for evaluation of acid generation and/or leaching potential of mine rock to be produced, and for assessment of existing rock piles. While this document focuses on mine rock, the rock classification, prediction testing and water quality modelling are also applicable to assessments of other components of the site: mine workings (pit walls, underground development), ore and low grade stockpiles, roads or other facilities constructed with coarse mine rock, and to a degree, tailings. The more homogeneous physical and geochemical nature of tailings, with finer particle size, closer proximity of the mineralization, and generally saturated deposition in a confined area generally makes prediction testing somewhat simpler.

The quality of water drainage from each component of a mine operation is really the key factor in evaluating environmental impact from mining operations. This is true at any stage of mine development, from pre-mining through to closure. Prediction testing therefore must accurately address all potential sources of contaminants, but the level of prediction must be appropriate to the amount of information available and the nature of the concerns.

The current approach to prediction of drainage quality is partly empirical and site and rock type specific; laboratory tests are used to simulate acid generation reactions within a mine rock pile and to estimate drainage quality from representative rock samples. This testwork is conducted using standard laboratory test procedures and typically does not attempt to simulate all field

conditions. The predicted drainage quality, based on some assumed relationship between test values and field conditions, can then be used in a dilution or mixing model to predict the overall water quality issuing from the mine rock disposal area.

Prediction testing should be conducted as part of the development of a mine rock management plan: to identify "problem" materials and develop suitable disposal techniques. Prediction and assessment should continue throughout the operating mine life; to identify material classes as rock is generated and ensure that materials which are potential sources of contaminants are managed for control of drainage water quality (Chapter 6). The approach to a prediction testing program for a new mine, or an existing mine is shown in Figure 5.1.

Pre-mine predictions for a new mining operation can realistically only be "estimates" of the drainage water quality. Prediction technology has developed to the point where approximate quantitative predictions of water quality and chemical loading can be made, recognizing that any assessment of long term potential is based on a limited time period of testing with a number of simplifying assumptions. The role of modelling in long term prediction is discussed in Chapter 7. For existing operations, quantitative predictions can be made more confidently, particularly where there is an understanding of the geochemical nature of the mine rocks and where contaminated drainage is evident.

This chapter addresses the prediction of acid generation and metal leaching potential from mine rock. It is important that this evaluation is completed in a staged program to maximize the information obtained, ensure that each test is addressing a relevant concern, and that all potential concerns are identified. Data should be evaluated during each stage of testing, to identify gaps in information and determine the direction and emphasis of any further work.

## 5.2 Objectives

There are two main objectives or stages in prediction testing:

i) material characterization to identify the acid generation and/or leaching potential and to estimate the level of control required; and,

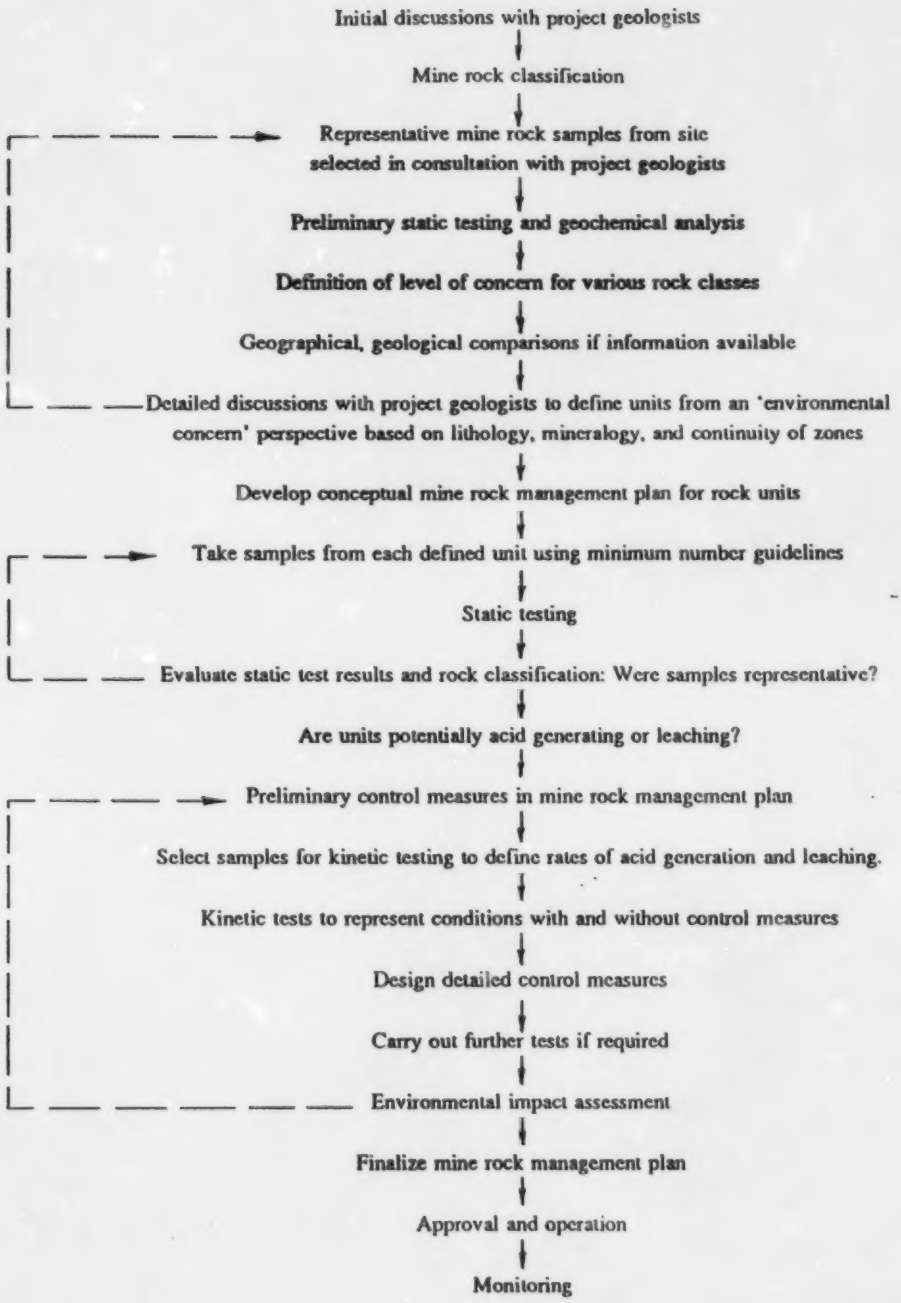

Initial discussions with project geologists
Mine rock classification
Representative mine rock samples from site selected in consultation with project geologists
Preliminary static testing and geochemical analysis
Definition of level of concern for various rock classes
Geographical, geological comparisons if information available
Detailed discussions with project geologists to define units from an 'environmental concern' perspective based on lithology, mineralogy, and continuity of zones
Develop conceptual mine rock management plan for rock units
Take samples from each defined unit using minimum number guidelines
Static testing
Evaluate static test results and rock classification: Were samples representative?
Are units potentially acid generating or leaching?
Preliminary control measures in mine rock management plan
Select samples for kinetic testing to define rates of acid generation and leaching.
Kinetic tests to represent conditions with and without control measures
Design detailed control measures
Carry out further tests if required
Environmental impact assessment
Finalize mine rock management plan
Approval and operation
Monitoring

Figure 5.1 Approach to Evaluating Potential for Acid Generation and Metal Leaching

ii) prediction of the drainage water quality from the mine rock under both uncontrolled and controlled conditions.

The material characterization is accomplished through visual description, sample analysis and static testing. Prediction of drainage water quality however is considerably more complicated, and requires kinetic testing to simulate the reaction and drainage processes over time, with the results being calibrated to actual site conditions, where possible.

There are a number of techniques that can be used in the prediction of acid generation potential and/or drainage water quality which will be discussed in this chapter:

- geographical comparisons (Chapter 5.3);
- geological models (Chapter 5.3);
- geochemical static tests (Chapters 5.6 and 5.7);
- geochemical kinetic tests (Chapter 5.8);
- mathematical models (Chapter 7.0).

## 5.3 Geographical and Geological Comparisons

These techniques for the assessment of acid generation potential which may be useful in the early stages of evaluation. Comparisons with sites with similar geographical or geological settings may provide a preliminary indication of the potential "level of concern".

Much of the early work in prediction of acid mine drainage was done in the coal mining regions of the Eastern U.S. In these areas homogeneous coal seams could extend for several tens of kilometres, and geographical comparisons were useful and valid. With hard rock mining however, significant variations in mineralogy and occurrence can occur within distances of several metres limiting the value of geographical comparisons. Regional similarities do exist such as with the "porphyry copper deposits of British Columbia", the "uranium deposits of Elliot Lake", and the "uranium deposits of Saskatchewan". Therefore, geographical comparisons may be useful in the initial assessment of a site, ie. "might there be a problem".

Geological comparisons can be useful for preliminary indications of leaching and acid generation potential. This type of comparison is based on the assumption that similar paleoenvironments mineralogical and geologic characteristics have similar potentials for leaching and oxidation, given similar climatic conditions.

Geological comparisons can be particularly useful if applied on a specific site basis, but caution must be used if comparing similar geological units at different sites. There are a number of factors other than the geological and mineralogical nature of the mine rock that control the rate and extent of metal leaching and acid generation (temperature, precipitation, dry/wet seasons) that can vary from site to site. These climatic and topographical influences can make comparison of drainage water quality from one site to another difficult to interpret. Within any one site however, the geological and mineralogical nature of the sample can be a valid basis for mine rock classification, as discussed in Chapter 5.5.

To make comparisons based on the geological and lithological nature of the rock, there must be a common basis (classification) for comparison. Such a classification should include mineralized occurrences, oxidation state of the minerals, sulphide type (mineralogy, crystal structure and size), sulphide distribution or exposure, alkali type and distribution, and tendency for the rock to slake or weather.

A classification system is discussed in more detail in Chapter 5.5. Such a classification is not typically part of the orebody evaluation, which is based on economic mineral characteristics, but can readily be incorporated into the preliminary evaluation and exploration programs. It would be useful to build up a database within Saskatchewan to refine geological classification in terms of oxidation and leaching potential, to assist in preliminary site evaluations. Preliminary classification work has been initiated by two mining companies in northern Saskatchewan for the development of mine rock management plans for further mining and for the assessment of current mine rock piles.

## 5.4 Sampling

Sampling is perhaps the most critical aspect of the prediction program. Samples must be representative of all geologic and lithologic units related to the mine development plan, and

representative of the relative amounts of each type of material. The units must be defined on the basis of physical and geochemical homogeneity. Samples must also be representative in terms of particle size distribution for the mine rock which will be produced. Surface area directly affects the rate and extent of leaching and ARD from mine rock. As finer particles have a greater surface area than the same mass of a larger particle size, the proportion of the finer fraction must be quantified and sampled for testing. As a general rule of thumb, the minus 10 cm fraction of the mine rock will probably produce the majority of the contaminant load and is a reasonable size for laboratory testing.

Although the collection of representative samples from geologic units is simple in concept, the implementation of the sampling program is more complicated and can be an iterative process, requiring at least two stages of sampling and static testing. Static tests on samples from a defined geologic unit may indicate significant spatial variability in acid generation potential. This variability may be spatially correlated and may indicate that the unit actually consists of two or more units in terms of acid generation and/or leaching potential. Additional units should then be defined and further samples collected to confirm the homogeneity of the new units. Such an iterative sampling and unit subdivision program may be preferable to the definition of the entire geologic unit as acid generating, requiring special handling and control/treatment techniques for the entire unit.

At least two stages of sampling and static testing are generally required for a new site. For an existing site, the extent of sampling and testing will depend on the available information and the familiarity of site personnel with the geology and distribution of mine rock around the site. Typically one or two sets of samples are required from the working areas (pit walls, underground workings) to identify the rock units and identify characteristic factors which will enable correlation of the rock classes with the material which has been deposited in the rock piles. The next stage of sampling would be from the existing piles, to determine the classes of mine rock that have been placed in each of the piles and collect appropriate samples for kinetic testing. This is necessary for the prediction of drainage water quality and evaluation of short and long term control measures from existing piles.

Uranium mines in northern Saskatchewan typically have two or more mine rock piles and, in most cases, will also have 'special waste' piles. The separation between 'mine rock' and 'special

waste' is based on uranium content, and does not directly reflect other mineralization which will determine the geochemical nature of the rock and therefore the potential for acid generation and/or metal leaching. For most of the existing mines there is little or no record of the rock types or quantities of mine rock that have been placed with respect to ARD potential, and therefore two stages of sampling are generally required:

i) sampling of distinct units from working areas to characterize mine rock types; and,

ii) pile sampling to determine extent of oxidation, storage of oxidation products, and rock classes within each pile.

The number of samples to be collected for each unit will depend on the stage of the testing program, the mass of rock, the level of concern and the heterogeneity of the unit. A curve indicating the recommended minimum number of samples required to characterize each geological unit in terms of acid generation and leaching potential was developed, based on data for a limited number of sites in British Columbia (SRK et al., 1989) as shown in Figure 5.2. This curve is based on preliminary data and should only be used as a guideline. If preliminary analysis and mine rock classification (Chapter 5.5) indicates a high degree of variability as a trend across the unit it may be appropriate that it be divided into two or more units, using the classification system, and additional samples taken using the minimum guideline presented in Figure 5.2.

The size of each individual sample must be based on the heterogeneity of the unit. As a general guideline, the sample size from a homogeneous unit (ie. evenly distributed or disseminated sulphide and alkali mineralization) should be at least twice the amount needed for the test. For static testing however only a small sample is needed for analysis and minimum of 1 kg is recommended where small-scale heterogeneity exists, such as mineral distribution in veinlets, a larger sample may be required to account for the small-scale regular heterogeneity.

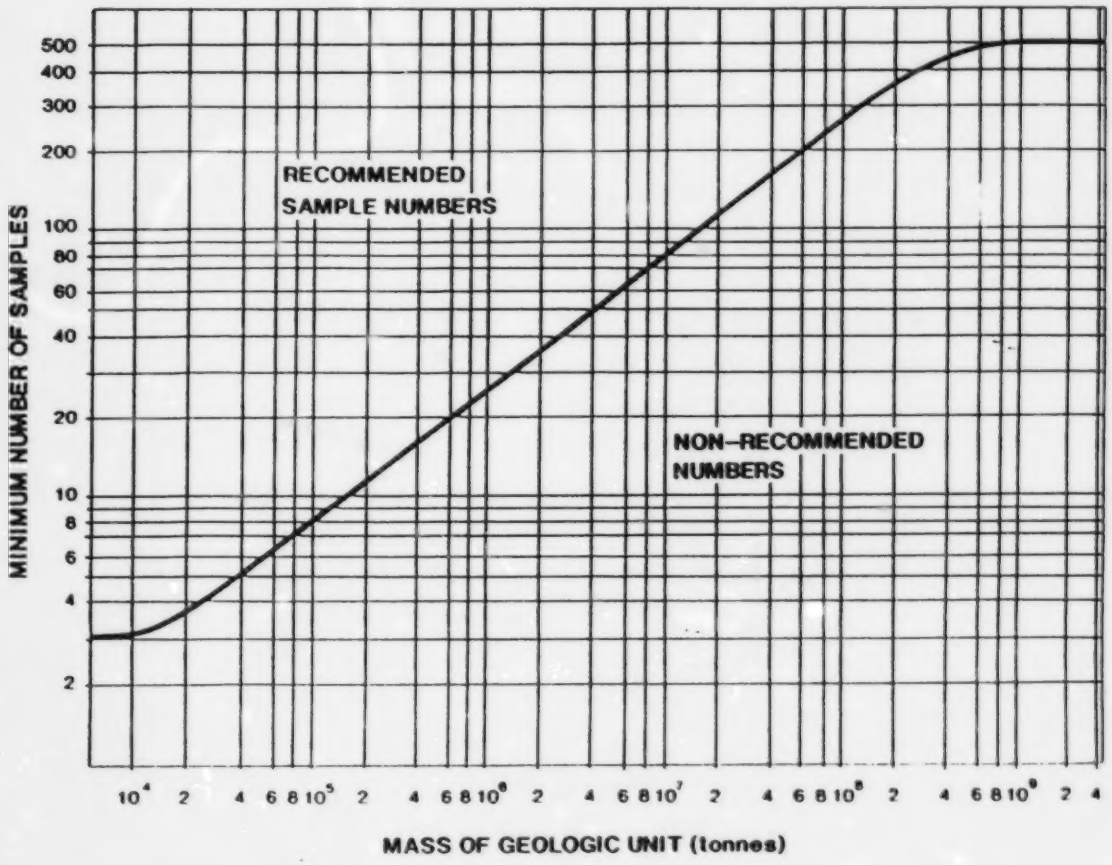



Figure 5.2 Recommended Minimum Number of Samples as a Function of Mass of Each Lithologic/Classification Unit (after SRK et al., 1989)

The potential sources for samples for assessment and prediction testwork are summarized in Table 4.2. Samples for characterization of mine rock piles at new mines could be taken from:

- drill core;
- trenches;
- exploration adits; and,
- bulk sampling for metallurgical testing.

Additional drilling may be required for detailed prediction as generally, in the exploration stage, the drilling program is focused on orebody definition, not mine rock sampling.

For an existing mine, samples can be obtained from:

- drill core from exploration can be useful for indication of changes (oxidation) in the period since the rock was extracted;
- additional drilling;
- pit walls;
- underground workings;
- existing ore stockpiles; and,
- existing mine rock piles.

All samples should be well labelled with location and type of sample. Sample locations should be noted on a site plan and staked or marked where practical, logged in the field using the classification system, and sample locations photographed. Ideally samples should be stored in a cool, dry environment to limit any weathering before testing. Prior to shipping the samples should be scanned for radioactivity to ensure they are compliant with shipping regulations.

In summary, the key points to consider in development of a sampling program are:

- define the geology, mineralization;
- consider the mine plan;
- consider all sources of samples;
- conduct an initial sampling program;

- classify the mine rocks; and,
- perform further sampling and reclassification if necessary.

## 5.5 Mine Rock Classification

The objective of mine rock classification is to identify units which are relatively homogeneous with respect to potential acid generation or leachability. Separate disposal strategies may be required for some of these units, and the classification system provides a simple tool for waste management. Classification is a method by which to identify different materials as they are (or will be) produced and dispose of them appropriately. To determine into which class each of the lithological/alteration/mineralization rock units identified for the site belong, the potential for leaching and acid generation must be determined. Experience has shown that a system which uses visual observation and classification of the physical and geochemical nature of the sample, together with relatively simple laboratory analyses (static testing) can be an effective tool for both design and operation of the waste management plan.

The classification of mine rock according to the visual physical and geochemical characteristics is intended as a tool to:

- represent the tendency or probability of a rock type to generate or consume acid or leach metal contaminants;
- provide a tool for interpretation of kinetic test results;
- provide a field tool to identify relatively homogeneous rock units with respect to drainage water quality as distinct geological units; and,
- supplement ABA and kinetic test results.

Once correlated with kinetic prediction test results, the system can provide a field tool for classification of mine rock types for appropriate disposal. As a predictive tool it provides a framework for understanding differences in reaction rates of different samples and for predicting which rocks may generate contaminants at some future time. To serve as a waste management tool it must first be calibrated using laboratory and field tests before it can be used as a field guide.

The structure of the rock classification system that has been developed primarily for acid generation potential is shown in Table 5.1. It is based on six key rock index properties: sulphide type (reactivity), and sulphide surface exposure, alkali type and alkali surface exposure, grain size, and slaking characteristics. The relative influence of each of the parameters is accommodated through weighting factors. Since the neutralizing capacity of the alkaline material prevents acid generation, the weighting factors are negative. There are other factors which affect the rate of acid generation and metal release, such as bacterial action, flushing rate and temperature but these are site specific rather than specific to rock type.

For sites at which there is no potential for ARD, this classification system is not appropriate. If the complexity of the site mineralogy and geochemistry requires some form of rock classification, the system would need to be modified to address the minerals which are the sources of contaminants. The alkali minerals which provide neutralization potential however would still be important in evaluating neutralization and metal removal along the flowpaths within the rock pile. The weighting system for the six factors could be adjusted (based on testing) to recognize those factors which control drainage water quality; to emphasize alkali exposure and distribution, grain size (surface area) and slaking rather than sulphide occurrence.

The descriptions and rating used in the classification are based on a subjective evaluation of metal leaching processes in laboratory and field cases and are considered preliminary. Further sampling and testing will be required at specific mine sites to calibrate these weighting factors for such sites. This classification system was developed in British Columbia and, to date, has been used primarily for base metal mines.

Rock classes may coincide with geological units or rock types. However, in the uranium orebodies in Saskatchewan, it appears that the acid generation and leaching characteristics are more closely related to alteration units and distance from the orebody. Each waste type

TABLE 5.1

## Rock Classification of Geochemical and Physical Parameters for ARD Evaluations (after Brodie et al., 1991)

| FACTOR | HIGHEST CHEMICAL ACTIVITY = 5 | 4 | INTERMEDIATE CHEMICAL ACTIVITY = 3 | 2 | LOWEST CHEMICAL ACTIVITY = 1 | RELATIVE WEIGHT | HIGHEST ARD POTENTIAL | LOWEST ARD POTENTIAL |
|---|---|---|---|---|---|---|---|---|
| Sulphide Type | highly reactive; e.g. framboidal or fine grained (<5 microns) pyrrhotite | | moderate reactivity; e.g. coarse grained (5 - 100 microns) pyrrhotite, or fine grained pyrite, or equal amounts of 1 and 5 | | low reactivity eg. pyrite, massive crystals (>100 microns) | 6 | 30 | 6 |
| Proportion Sulphide Surface Area Exposure | localized (zones) of concentration exposed on fracture surfaces; e.g. >50% of sulphides in stringers or veins | | >20% of sulphides in zones, stringers or veins with some preferential exposure on fracture 5 | | individual small crystals uniformly distributed throughout rock host material | 5 | 25 | 5 |
| Alkali Type | highly reactive eg. $CaCO_3$ | | moderate reactivity | | slightly reactive | -4 | -4 | -20 |
| Proportion Alkali Surface Area Exposure | individual small crystals uniformly distributed throughout rock host material, or >50% alkali in bedding, fractures or veins which tends to become exposed in handling | | >20% of alkali in bedding or veins with some preferential exposure on fractures | | localized (zones) of concentration exposed on fracture surfaces; e.g. >50% of alkali in bedding, fractures or veins which tends not be become exposed in handling | -3 | -3 | -15 |
| Grain Size | >20% fines; e.g. >20% sand size or finer | | 5% sand size or finer, | | little fines; <1% sand size or finer | 2 | 10 | 2 |
| Weathering/ Slaking | highly slaking; >20% of rock mass degrades to sand size or finer | | slightly slaking; >2% of rock mass degrades to sand size or fumier | | non-slaking and durable rock; | 2 | 10 | 2 |
| | | | | | | Total | 68 | -20 |

NOTES:

1. The rating scale along the horizontal axis varies from 1 "lowest" referring to the combination of characteristics resulting in the lowest (if any) rate and production of acidic drainage, to 5 "highest" referring to the combination of characteristics resulting in the highest rate and production of acidic drainage.
2. The cumulative weighted point rating for the sample is plotted on the NP:AP graph defining boundaries of rock types for ARD prediction. Possible totals range from -20, consisting of massive pyrite crystals in a disseminated highly reactive base concentrated on exposed fractures with little fines and not slaking, to 68 rock consisting of highly reactive pyrrhotite, highly concentrated on exposed fractures and stringers in a low reactive base which is disseminated within the host rock with much fines and a high slaking potential.
3. Grain size estimates in sulphide type factor from Dophell 1989.

should be classified according to these characteristics. In latter stages of a program, testing is conducted to determine the "level of concern", or potential leachability of the different rock types. The characteristics of mine rock that appear to control leaching and acid generation from mine rock at Saskatchewan's uranium mines include:

Physical Characteristics

- degree and nature of alteration, particularly clay alteration;
- exposure or occurrence of mineralization, ie. disseminated or concentrated on joints, fractures or bedding planes;
- durability of the mine rock;
- grain size; and
- distance from the orebody. This may be a control on the metal concentrations and thus is included as a factor in chemical characteristics.

Geochemical Characteristics

- mineralogy, particularly the nickel and arsenic minerals;
- sulphide and metal content; and
- alkali content.

Once the ARD rating for a sample has been determined it can be compared with the results of laboratory tests performed on that rock type to develop a correlation between ARD rating and acid generation potential as predicted by laboratory tests.

## 5.6 Static Geochemical Testing

### 5.6.1 Introduction

The first stage in any testing program is to classify the rock units on the site with respect to the acid generating and leaching potential for the site and to collect representative samples for testing. Static tests are conducted on these samples to identify the rock units that may have the potential to generate acidity Solid sample analyses are conducted to quantify the metal content

of the rock. There are limitations however to the use of static tests for prediction. Static prediction techniques are useful as qualitative predictions only, and cannot be used to predict drainage water quality. Acid generation processes are dependent on a number of factors including a time and rate dependency, which are not addressed in static testing. Further tests are then required to determine the rate and severity of oxidation and acid generation, The rate and period of metal leaching and for the prediction of water quality.

### 5.6.2 Test Procedures

The first step in the analysis of samples for material characterization consists of a static test on each sample. These tests are simple, rapid and relatively inexpensive to conduct. A large number of tests can be conducted to characterize the mine rock, and from these to select samples for further (kinetic) testing.

Whole rock geochemical analyses or elemental analyses in combination with the mineralogical descriptions are also often carried out on selected samples at this stage. Based on theoretical understanding and testing of similar samples, it may be possible from these tests to estimate the relative potential for metal release, eg. if secondary weathering products which are known to be soluble in slightly alkaline or acidic environments are present, the sample could potentially generate contaminated drainage. A proposed whole rock geochemistry analysis suite as proposed in MPCB, 1990, is shown in Table 5.2.

A static test defines the balance between the potentially acid generating and potentially acid consuming minerals in a sample. Acid producing minerals are generally reactive sulphide minerals. Acid consuming minerals are primarily carbonate minerals although hydroxides, silicates, and clays can also provide neutralization potential. It was initially postulated that a sample will be a net acid generator only if the potential acidity exceeds the neutralization potential. This has since been shown to be erroneous and samples with an excess of neutralization potential may, in some circumstances, be acid generating.

**TABLE 5.2**
**Proposed Whole Rock Chemistry Analyses for Mine Rock**
**(after MPCB, 1990)**

| PARAMETER | TEST PROCEDURE | REPORTING UNITS |
|---|---|---|
| Radionuclides (Uranium Orebodies) | Require SRC type methods and detection limits, as per analyses done for Eagle Point Mine Rock | |
| Lead 210 ($Pb^{210}$) | | bq/g |
| Polomium 210 ($Po^{210}$) | | bq/g |
| Radium226 ($Ra^{226}$) | | bq/g |
| Thorium 230 ($Th^{230}$) | | bq/g |
| OTHERS | DETECTION LIMIT | |
| $Al_2O_3$ | 0.1% | % |
| $Fe_2O_3$ | 0.01% | % |
| CA0 | 0.01% | % |
| MG0 | 0.01% | % |
| $K_20$ | 0.01% | % |
| $Na_2O$ | 0.01% | % |
| $SiO_2$ | 0.1% | % |
| $TiO_2$ | 0.01% | % |
| $P_2O_5$ | 0.01% | % |
| Ag | 0.1 ug/gm | ug/gm |
| As | 0.2 ug/gm | ug/gm |
| B | 10 ug/gm | ug/gm |
| Ba | 1 ug/gm | ug/gm |
| Be | 1 ug/gm | ug/gm |
| Bi | 0.2 ug/gm | ug/gm |
| Cd | 0.1 ug/gm | ug/gm |
| Cl | ? | ug/gm |
| Co | 1 ug/gm | ug/gm |
| Cr | 1 ug/gm | ug/gm |
| Cu | 1 ug/gm | ug/gm |
| Fe | 1 ug/gm | ug/gm |
| K | ? | ug/gm |
| Mo | 2 ug/gm | ug/gm |
| Ni | 1 ug/gm | ug/gm |
| pb | 2 ug/gm | ug/gm |
| S | 0.002% | ug/gm |
| Sb | 0.2 ug/gm | ug/gm |
| Se | 0.2 ug/gm | ug/gm |
| Ti | ? | ug/gm |
| U | 0.1 ug/gm | ug/gm |
| V | 1 ug/gm | ug/gm |
| W | ? | ug/gm |
| Zn | 1 ug/gm | ug/gm |
| Zr | 1 ug/gm | ug/gm |
| % LOI | 0.1% | ug/gm |
| Ag | 0.001 ug/gm | ug/gm |
| Other rare earths? | 1 ug/gm | ug/gm |

A number of static test procedures have been developed to determine the proportions of acid generating and neutralizing minerals including:

- B.C. Research Initial Test;
- Alkaline Production Potential: Sulphur Ratio Test;
- Net Acid Production Test;
- Acid-base Accounting; and,
- Modified Acid-base Account.

Each addresses the same variables, but with variations in the procedures. The most commonly used static test procedure is acid-base, or modified acid-base, accounting (ABA). The potentially acid generating minerals (expressed as maximum potential acidity, MPA) and acid neutralizing minerals (expressed as neutralization potential, NP) are determined by lab testing. The evaluation of metal leaching potential analysis in acid-base accounting is useful in understanding the potential for control of metal dissolution and migration by neutralization.

The general procedure for determining an acid-base account of a sample consists of three procedures:

1. Initially the sample paste pH is measured to determine the natural pH of the material, and to determine if acid generation has occurred prior to analysis. Generally, if the paste pH value is greater than 8 the sample probably contains reactive carbonates; if less than 5, there has probably been acid generation in the sample or surrounding material.

2. The total sulphur content and sulphur species of a sample are measured, and the maximum potential acidity as sulphuric acid calculated. Total sulphur is typically measured using a Leco furnace sulphur analyzer. Sulphur species are determined using different digestion and precipitation procedures (APHA, 1985).

   The maximum potential acidity is calculated from the sulphur content. Calculation of acidity from total sulphur content may overestimate the amount which is actually acid generating as sulphur present as sulphate will not contribute to acid generation. Sulphur

species, or reactive sulphide content, may be determined and the sulphide content used for estimation of potential acidity.

3. The third part of the analysis is the determination of neutralization potential using a base titration procedure of a pre-acidified sample. A "fizz test" is first done to estimate the amount and strength of acid required to react with all of the acid consuming materials present in the sample. In the EPA procedure (Sobek et al., 1978) the sample is treated with excess standardized hydrochloric acid and heated to ensure complete reaction. A modification of the procedure has been suggested in which the acidified sample is not heated, but agitated for 24 hours. After the acidification is complete, the unconsumed acid is titrated with a standardized base to pH 7 (often in two or three stages) and the equivalent calcium carbonate of the acid consumed is calculated. An alternative procedure, the B.C. Research Initial Test, is a direct sulphuric acid titration of the sample from natural pH to an endpoint of pH 3.5.

### 5.6.3 Reporting

The maximum potential acidity (MPA) or acid potential (AP) of a sample based on the total (or sulphide) sulphur content can be calculated by:

$$AP = \% \text{ sulphur} \times 31.25$$

The result is expressed in terms of kg $CaCO_3$ equivalent per tonne of sample.

The neutralization potential (NP) is calculated from the mass of sample and volume and normality of the acid and base added. AP is expressed in terms of kg $CaCO_3$ equivalent per tonne of sample. The net neutralization potential (NNP) of a sample is given by:

$$NNP = NP - AP$$

The results of each acid base accounting test should include:

- sample description;
- paste pH;
- sulphur analysis - total and sulphide species, if conducted;
- calculated NP, AP, NNP; and,
- ratio of NP/AP.

Detailed procedures, including calculations and presentation of results, for the U.S. E.P.A. standard method are available in the literature with the specific reference in "Field and Laboratory Methods Applicable to Overburden and Minesoils", EPA-600/2-78-054, 1978. Descriptions of this and the modified procedure, and other static prediction methods and options are available in the Draft Technical Guide, (SRK et al. 1989) and described in more detail in the Acid Rock Drainage Prediction Manual (Canmet-MEND, 1990).

### 5.6.4 Interpretation

The interpretation of static test results is based on both the difference and ratio between the acid potential and neutralization potential. The difference between the maximum potential acidity and the gross neutralization potential gives the net neutralization potential. Experience from the eastern US coal fields in the interpretation of acid generation potential from ABA results is shown in Figure 5.3, where theoretically a sample is net acid generating if the NNP is less than zero. US coal field experience has shown that values of NNP between -20 and +20 tonnes $CaCO_3$/1000 tonnes of sample (-2 to +2 % $CaCO_3$) may be acid generating. This range of uncertainty can be attributed to errors inherent in the test procedures, conversions to total acidity, analytical error and small sample size.

More recent experience in the evaluation of mine rock piles at Canadian metal mines has shown that in addition to the NNP value, the ratio between the NP and AP should also be considered. As shown in Figure 5.4, samples with 3 times the neutralization potential to the potential acidity can be considered acid consuming. Samples with less than a 1:1 ratio are probably acid generating. Between these ratios however samples are neither clearly acid generating or acid consuming due to other factors which influence acid generation potential.

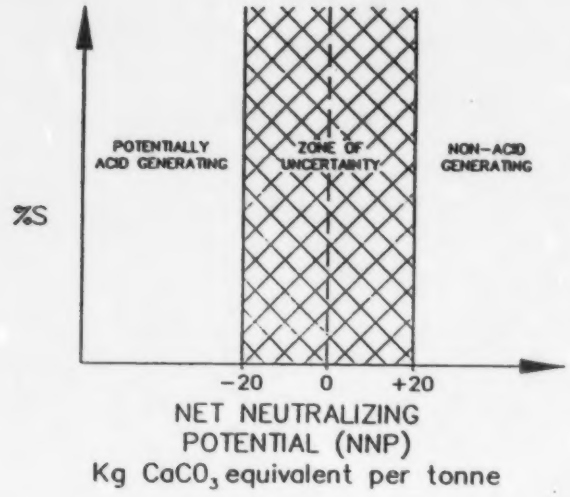



**Figure 5.3** Interpretation of Acid-Base Account Results Based on NNP for Eastern US Coal Mines

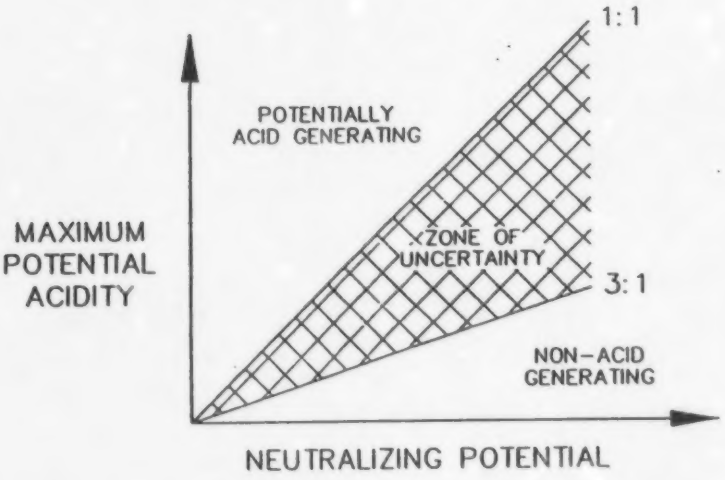


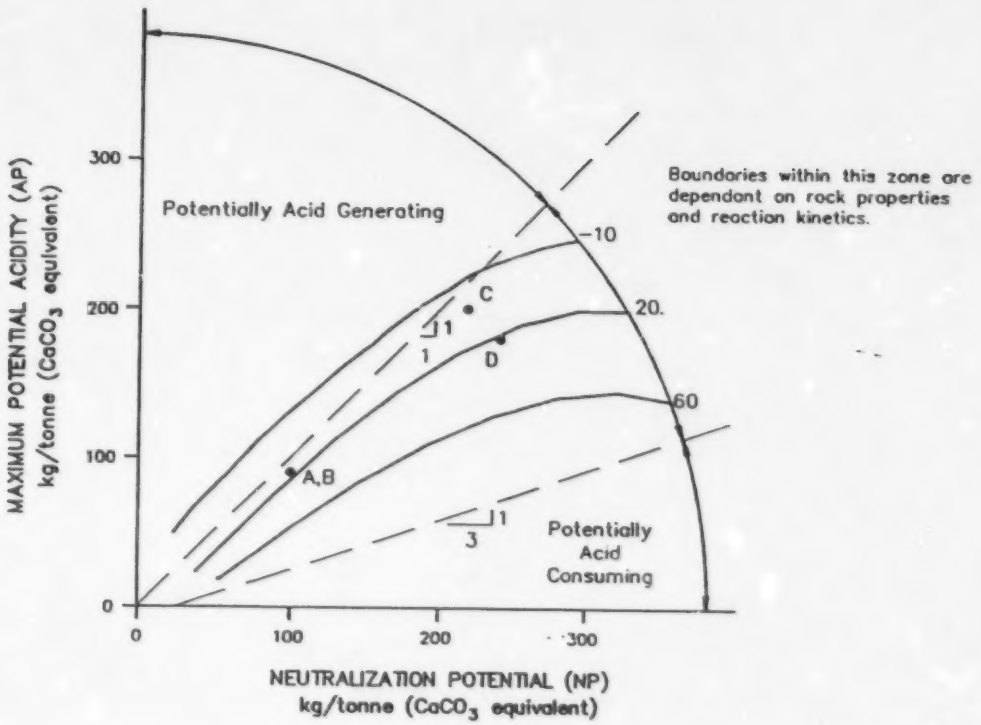

**Figure 5.4** Interpretation of Acid-Base Account Results Based on NP:AP Ratio for Mine Rock at Canadian Metal Mines

For tailings, a ratio of 1:1 and a positive NNP which satisfies Figure 5.3, may acceptably define non-acid generating tailings. The ratio of NP:AP is the primary indicator of acid generation potential for mine rock, in static tests.

For mine rock, however, the large particle size can result in physical separation of the alkali minerals (acid consuming) from the sulphidic minerals (acid producing). The surface area exposure of sulphide and carbonate or neutralizing minerals is of particular relevance in mine rock which is inherently heterogenous due to the coarse particle size and variability in source rock. Concentrations of mineralization may result in a disproportionately large exposure of sulphide minerals on the rock particle surfaces and non-intimate contact or mixing of acid generating and acid neutralizing minerals. Therefore while the overall sample may have a positive NNP, the physical separation of the NP and AP may result in a low pH, contaminated seep from parts of that sample. A NP:AP ratio of greater than 3:1 is generally accepted as defining acid consuming material in B.C. for waste rock on a mine block basis. Kinetic testwork and sample classification is required to demonstrate that lower ratios are acceptable for certain classes of rock at a site. It is for samples in this range that the rock classification system is most important: to clearly identify mine rock which requires control measures to ensure acceptable drainage water quality.

Figure 5.5 illustrates the use of the ARD rock classification system to reduce the area of uncertainty. Hypothetical lines corresponding to ARD classification of -10, 20 and 60 are plotted on this figure. The position of the line reflects the boundary between samples of that ARD rating group which are potentially acid generating, and samples which do not present an acid generation induced drainage water quality problem as determined by kinetic testing. Two samples with the same ABA value but different physical or geochemical natures (hence different ARD ratings) may produce quite different drainage water quality. For example, the clay altered Athabasca sandstone unit can be a ready source of particulates and be rapidly oxidizing compared to a sample of the more competent Peter River Gneiss rock (with the same ABA value).

Four examples are shown in Figure 5.5. Sample A has an NP of 100, an AP of 95, and an ARD rating of 60. It plots above the ARD rating line equal to 60 and therefore is considered acid generating. Sample B has an NP of 100, an AP of 95, and an ARD rating of -10. It plots




EXAMPLES

| | AP | NP | ARD RATING | PREDICTION |
|---|---|---|---|---|
| A | 95 | 100 | 60 | POT. ACID GENERATION |
| B | 95 | 100 | -10 | POT. ACID CONSUMER |
| C | 200 | 220 | -15 | POT. ACID CONSUMER |
| D | 180 | 240 | 65 | POT. ACID GENERATION |

Figure 5.5 Conceptual Mine Rock Classification for Mine Rock Management Planning

essentially at the ARD rating line equal to -2, ie. below the location of the ARD line equal to -10, and is expected to be acid consuming. Sample C has an NP of 220, an AP of 200 and an ARD rating of -15. It is predicted to be acid consuming.

The ARD rating lines plotted on Figure 5.5 are for illustrative purposes only and have not been determined for Saskatchewan mine rock. Also, the indication that a rock type is not acid generating is not an indication that contaminated seepage will not occur. Contaminant leaching can occur from non-acid generating rocks which contain contaminants which are soluble at neutral pH.

In summary, static testing defines the theoretical potential for production of net acidity based on the balance between potentially acid generating and potentially acid consuming minerals. These test are relatively simple and rapid to do and should form the basis for any test program. Interpretation of results should be based on the net neutralization potential and the ratio between NP and AP. For a mine rock a NP:AP ratio of greater than 3:1 on a mine rock sample would indicate a net acid consuming sample. The steps in the testing procedure and interpretation are summarized in Figure 5.6.

## 5.7 Leach Extraction Tests

Short term leach extraction tests are used to determine the readily soluble component of a sample. There are a number of different test procedures which vary primarily in the duration of the test and the nature of the extractant. These tests are useful in the initial phases of testing program to indicate the short term leaching characteristics and potential for metal release from a sample in the absence of acid generation. These tests can also indicate the extent to which oxidation and acid product storage has occurred in a sample and are particularly useful for the evaluation of existing mine rock piles, and mine rock which contains readily soluble contaminants.

There are a number of procedures; typically, the sample is combined with water or a weak acid in a 1:20 ratio and gently agitated to maintain the solids in suspension for 18 to 24 hours. Solution pH may be monitored or adjusted periodically, and the final leachate analyzed for such parameters as pH, Eh, conductivity, sulphate, alkalinity, acidity, and metals. These tests provide an indication of the readily soluble load in a material, and of the extent of acid generation that

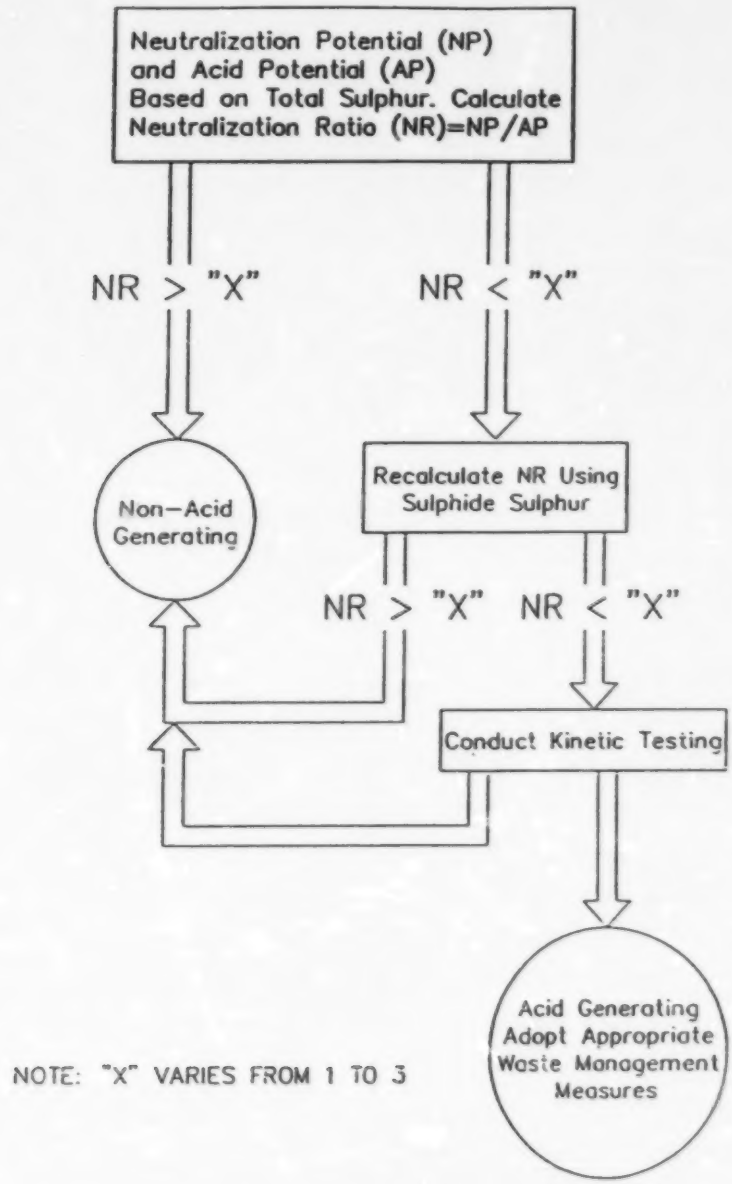



Figure 5.6 Approach to Static Test Result Prediction and Interpretation

has already occurred in the sample. This load would be primarily a short term water quality concern, released from the mine rock soon after placement in the rock pile and exposed to precipitation leaching.

Numerous laboratory test procedures have been introduced in Canada and the United States over the years, all of which have the objective of quantifying the mobility of the contaminants and thereby enabling the classification of the material for the appropriate method of disposal and containment requirements. Such tests have a variety of names such as B.C. Special Waste Extraction Procedure, TCLP, EPA 1312, ASTM 3987, WET Test and so on. While the objective of each of the tests is the same, the procedure and thus the relevance of the results of mine rock varies for each test. Some of the more commonly used tests include:

- ASTM D3987 distilled water extraction;
- B.C. Special Waste Extraction Procedure (SWEP) using an acetic acid extractant;
- U.S. EPA 1312 procedure using a nitric/sulphuric acid extractant;
- U.S. EPA 1311 or TCLP leach test using acetic acid based extractant.

Most of the studies evaluating the relative merits and applicability of each test have concentrated on the hazardous waste applications. Two such studies are documented in the literature, and a study is currently in progress in British Columbia to evaluate the use of the above mentioned tests for use on mine rock and tailings. At this time it appears that the EPA 1312 test (designed for mine soils and overburden) and a distilled water or site water shake flask extraction procedure similar to the ASTM 3987 are the most applicable tests. There is growing recognition that acidic acid leachant may not be appropriate for arsenic, copper and lead extraction. However, for all of these procedures it must be recognized that the fine sample particle size and short duration of the test do not represent field conditions and the results can be very difficult to relate to the field behaviour. The results of these tests indicate the total soluble load for the crushed or ground sample. To quantify the stored oxidation products, it is suggested that a modified D3987, EPA 1312 or other test be used, but on an uncrushed sample. The sample will need to be relatively fine (-10cm), and the proportion of the mine rock this sample represents must be quantified.

## 5.8 Kinetic Testing

### 5.8.1 Introduction

The objective of static tests (Section 5.6) is to identify the geologic units at a site that may have the potential to generate net acidity and quantify the metal/salt contest which may be leachable. The objective of kinetic testing is to confirm the acid generation potential with greater accuracy and to predict the short-term and long-term drainage water quality in the field. Geochemical kinetic tests involve weathering, under laboratory controlled or on-site conditions, of samples of rock units in order to confirm their potential to generate acidity, determine the rates of acid generation, sulphide oxidation, neutralization, and metal depletion and to test control/treatment techniques.

Information on the relative rates of reaction is critical to the design of a mine rock management plan and acid drainage control technology because, for example, the rate of acid generation may be negligible, or in extremely rare cases, may be severe for only a short period of time so that long-term control or treatment techniques may not be necessary. Based on the results of kinetic tests, treatment and control techniques can be selected that are appropriate to the severity and extent of acid generation specific to a geologic unit. Low volumes of a mildly acid generating unit might be mixed with other rock units. Alternatively, high volumes of strongly acid generating material will require control during operation and after closure, and possibly long term contingency measures.

### 5.8.2 Objectives of a Kinetic Test Program

Geochemical kinetic testing is the third stage in a prediction or site assessment program. After the mine rock has been classified, and static testing completed, samples can be selected for kinetic testing. Whereas static tests provide some information on overall potential acid generation, independent of time, kinetic tests explicitly define reaction rates for both metal dissolution, and acid generation and leaching through time under specific conditions. As a result, kinetic tests are more expensive and can continue for months or years. The objectives and scope of kinetic testing must be well defined to develop an efficient and effective test program. Ultimately, true prediction of long term drainage quality will only be possible through

quantitative mathematical models which can reliably extrapolate results beyond the time of the tests (Section 2.6).

The nature of the samples, and the number of tests required will depend on the objectives of the program. Kinetic prediction testing for a new mine is carried out to:

- validate static test results;
- compare leaching behaviour of different mine rock classes or types;
- predict drainage water quality from rock types and rock piles;
- select or confirm disposal and control options;
- represent site conditions to determine factors controlling ARD, and produce raw data for modelling.

For an existing mine the prediction and assessment program can be used both to predict the potential for contaminant generation from further mining, and prediction and of:

- extent of oxidation that has developed within the rock piles;
- the stored oxidation products within the rock pile to estimate the long term potential for flushing and release of contaminants, even without further acid generation or without incorporating any control measures;
- effectiveness of control measures;
- drainage water quality.

A well designed prediction program can provide not only a measure of the extent to which there is a contaminant migration problem, but also the future rate and potential for contamination. This information is necessary for assessment of closure requirements and costs, and also to refine monitoring programs.

Once the objectives of the program are established, samples can be selected for kinetic testing. Typically these samples will include:

- samples which have a readily soluble component (from static or short term leach testing);

- samples with NP:AP ratios between 3:1 and 1:1, the range in which the samples are not clearly acid generating or consuming;
- acid consuming sample(s) for testing of acid consumption and "natural treatment" of acidic drainage in situ; and,
- selected acid generating samples for evaluation of contaminant release and control measures.

### 5.8.3 Geochemical Kinetic Prediction Test Techniques

There are a number of techniques that are used, or proposed for use, for kinetic testing:

- B.C. Research confirmation test;
- shake flask weathering test;
- soxhlet extraction test;
- humidity cell and modified humidity cell tests;
- large scale modified humidity cell tests (SRK cells);
- column leach tests; and,
- field test plots.

Both the small scale controlled tests (for example humidity cells) and large scale on-site weathering trials have been used in assessing acid generation and drainage water quality. The controlled tests have the advantage of maintaining known constant conditions, but they are not necessarily representative of field conditions. On-site tests may be considered more representative than controlled tests because of the natural climatic conditions under which the tests are conducted; however, since results vary as climatic conditions change, the interpretation and extrapolation of the test results is more complicated.

Kinetic tests are used for prediction of drainage water quality both as a result of dissolution of readily soluble constituents, and as a result of oxidation and metal leaching. The understanding of which process controls the drainage water quality is based on interpretation of the test results, as discussed in section 5.8.5.

There are some tests for which standard procedures have been established and documented. These test procedures will be summarized in the following section and appropriate references noted. However, there are some tests which have been modified in terms of procedures or interpretation of results, and these will be discussed in more detail.

*Humidity Cell Testing*

Conventional humidity cell tests are small scale laboratory tests designed to simulate the processes of geochemical weathering for a specific rock sample under optimum, but not necessarily field representative, oxidation conditions. The testing is conducted in a special apparatus in which temperature, airflow and humidity can be controlled. Oxidation products are periodically flushed from the cell and analyzed. The data from the humidity cell tests can be used to evaluate the relative rate of release of oxidation products, the potential extent of weathering, and to estimate the lag to acid generation.

The test procedure is based on weekly cycles in which the sample is subjected to alternating cycles of dry and moist air (three days each) and 1 day of flushing and testing of the leachate. The sample is placed in an enclosed chamber, either PVC tubing approximately 20 cm diameter with the height varying with the amount of sample, and type of material to be tested or a rectangular plastic container. The sample may rest on the bottom of the cell, or be placed on a screen above the bottom of the cell to allow an upflow of air through the sample. Various modifications of the technique include inoculation with an active bacterial culture (*Thiobacillus ferrooxidans*), humid air passing upwards through the cell, and the relative solid/flush volumes and frequency of sampling. Typical parameters which are monitored include pH, redox potential, acidity, alkalinity, sulphate, conductivity, and dissolved metals.

The length of time for which the test is continued will vary with the results of the weekly flushing, and the objective of the test; ten weeks is considered the minimum test duration, but 70% are required to run for periods of 20 weeks or longer to achieve maximum rates of acid generation. The lag time until acid production is evident will depend on the net neutralization potential of the sample, as indicated by acid/base accounting, and the availability of the carbonate and sulphide minerals. Initially the rate of release of sulphate (from the oxidation of sulphides), and the release of alkalinity and changes in acidity provide an indication of the reaction process

and hence the lag time until the onset of rapid, biological oxidation and acid generation. As pH decreases below 5.5, changes in other parameters will become more rapid; conductivity and redox potential generally increase, and elevated acidity and dissolved metal levels become more apparent.

The tests do not address site specific conditions, and provide only semi-quantitative information about predicted water quality. The procedure is conducted on crushed or ground samples and therefore does not address the influence of particle size or relative spatial distribution of sulphide and base minerals, particularly for mine rock. These tests are generally considered more representative of the behaviour of finely crushed, well mixed and essentially homogeneous material such as mill tailings. There is also some concern that complete flushing of the sample on a weekly basis is not representative of field conditions, except in certain specific climates and field conditions, and may significantly alter the development of local low pH environments and the natural storage and flushing of oxidation products. The local environments which develop in the test cell and the physical and chemical effects of storage and flushing have a large effect on the acid product generation and quality of drainage in the field.

*SRK Modified Humidity Cell*

The objective of this test method is to provide a laboratory method which will predict more closely the drainage water quality (not just acid generation potential per se) from rock piles. The data would be used in the development of mine rock disposal plans and predicted water quality draining from the rock piles in both the short and long term. The test should model conditions in the rockpile and the leaching conditions to which it will be subjected. Specific issues which were considered in the development of this test method are:

- representative particle size distribution of the material tested, which can be scaled to the distribution (of the minus 10 cm diameter particles) in the rock pile;
- variability of sulphide and carbonate mineralization, surface area exposure, and physical distribution occurring in the rock pile;
- geochemistry of localized zones of rock and their variability on the scale represented by larger mine rock particles (on a scale of a few centimetres or more);

- representative testing of the physical and geochemical nature of a proposed rock pile (eg. particle size surface area exposure, mineralogical surface area exposure), occurring along discrete flow paths subject to seepage flow variations characteristic of what would occur in the field;
- prediction of drainage water quality from a rock pile considering:
  - the individual zones and rock types within a rock pile,
  - reactions along the drainage flow path, including ARD product concentration and shortage,
  - the resultant drainage quality from seepage through a combination of individual zones within a rock pile, and,
  - the seasonal range of concentrations resulting from varying flow rates, wetting and drying periods, and storage of oxidation products within a rock pile; and,
- design of tests to establish the acid consuming/acid generating nature of the material and provision of data for prediction of drainage quality within a reasonable period of time.

The equipment which has been developed and used to date for these tests generally consists of a small column, approximately 30 cm in diameter to accommodate material with a particle size distribution of minus 10 cm. The material rests on a perforated plate to allow drainage and air is introduced at the sides or bottom of the cell. SRK humidity cells should be conducted under the same temperature conditions as conventional humidity cells with a constant flow of humidified air.

In the SRK humidity cells, the flushing is limited and is directed along discrete flow paths in the cell to eliminate complete rinsing of the sample each cycle and allow the natural storage of oxidation products between and adjacent to flow paths. Flushing should be done by drip feeding water over extended periods to simulate infiltration and flow through dumps. The volume of flushing water is limited to approximate field estimated rates (per square metre) although it may be increased to provide an adequate effluent sample for testing. By comparison, conventional humidity cell tests are conducted on a weekly cycle with alternating cycles of three days of dry air, three days of moist air and then a complete flushing of the solids with distilled water. In the conventional cell, this flush is intended to completely remove all oxidation products, and significantly alters the chemical environment of the test specimen.

Water sampling is conducted weekly, however complete analysis of the samples (including ICP of the leachate) may only be required biweekly during the initial stage of the long term tests. Sampling every week may be required once pH drops below 5, or more rapid changes become evident in other parameters.

*Column Leach Testing*

Columns or lysimeters are also used to simulate geochemical weathering for prediction of acid generation potential, and drainage water quality. These tests are larger scale than conventional humidity cells, and larger particle size material can be used. More sample is required for these tests than for conventional or SRK modified humidity cells. Columns can also be used to test alternative disposal options and control measures.

As described in the Draft Acid Rock Drainage Technical Guide (SRK et al., 1989), column tests are conducted using a variety of columnar materials, such as PVC plastic, which are filled with the samples to a certain level or with a certain weight based on the specific objectives of the program. In general, a known amount of material is placed in the column and distilled water or water-based solution is flushed through the sample or ponded on top of the sample. Water samples of the flushing water or overlying pond water are periodically collected and chemically analyzed. Sampling ports can also be installed at intervals over the length of the column for intermediate sampling.

Some variations are:

- wet/dry cycles;
- degree of water saturation in the sample;
- fluctuating water table, or flooded conditions;
- flushing rate through the sample;
- water forced upwards through the sample;
- inoculation with bacteria;
- single pass or recirculation of the leachate; and,
- sample types, effect of blending.

Interpretation and presentation of the results of column tests is similar to humidity cell testing. Flushing of the sample is typically conducted as a constant flow and is sampled on a timed basis (daily or weekly) based on the rate of flow, or volume of leachate. Results must be interpreted accordingly. Dissolved and/or gaseous oxygen and carbon dioxide may also be monitored, depending on the nature of the test.

### 5.8.4 Procedures for Conducting Kinetic Tests

The initial step in a kinetic test is the definition of additional material characteristics to those measured in static tests. These characteristics are important to the interpretation of results from the kinetic testing and the prediction of drainage water quality. Before a kinetic test is initiated key information should be collected:

- mine rock classification;
- ABA characteristics;
- particle size distribution; and
- mineralogy, petrology.

During the test both the leachate or weekly flushing solution, and the rock should be observed for:

- leachate chemistry;
- leachate colour; and
- precipitates observed in cell or leachate.

The leachate chemistry analyses, that should be conducted for each test vary with the specific objectives of the test program, and the nature and mineralogy of the samples tested. All test programs should be designed and conducted in consultation with the site geologists. The sampling program and initial assays of the samples (from drill core and/or bulk sampling) should provide an indication of metals of concern, such as mercury or arsenic, which may need to be addressed in more detail than they would in the standard program.

At the conclusion of each kinetic test, the column or modified humidity cell should be flushed completely to remove any stored products and the solution analyzed. The solids should also be

removed from the column and sampled for analysis. At the conclusion of the test, similar analyses should be done as at the beginning:

- flush solution chemistry;
- ABA characteristics;
- particle size distribution;
- mineralogy, petrology; and,
- precipitates, coatings in cells.

Table 5.3 provides a summary of the common parameters that are measured for ABA, and humidity cell and column tests but is neither complete nor comprehensive for all tests. Standard analyses and measurement that should be conducted for all samples, for each test are listed. Additional procedures have also been recommended that may not be required on all samples, or all test programs, but should be considered.

### 5.8.5 Interpretation of Results

The results of the weekly analysis of the flush or leachate will indicate changes in solution and solid chemistry since the previous flush. The relative rates and sequence of oxidation will be indicated by changes in pH and conductivity, and calculations of production rates of sulphate, acidity, alkalinity and dissolved metals calculated in terms of sample weight and/or surface area. The information that should be tabulated for each cycle includes:

- sample description, cycle number, duration, leachate volume;
- readings or concentrations of all measured parameters;
- calculated acidity and alkalinity (mg/L $CaCO_3$ equiv.), sulphate (mg/L $SO_4^{2-}$) production;
- cumulative production of acidity, alkalinity, and metals (mg/kg or mg/kg/$m^2$); and,
- cumulative sulphate production (mg $SO_4^{2-}$/kg or mg $SO_4^{2-}$/kg/%S/$m^2$).

## TABLE 5.3
## Prediction Test Methods for Mine Evaluation

| TEST PROCEDURE | ACID-BASE ACCOUNT | LEACH EXTRACTION | CONVENTIONAL HUMIDITY CELL | SRK MODIFIED HUMIDITY CELL | COLUMN LEACH |
|---|---|---|---|---|---|
| Typical Analyses | • Total Sulphur - Leco<br>• Titration for NP<br>• Paste pH | **Solids**<br>• ICP before after test<br>**Solution**<br>• Dissolved metals | **Solids**<br>• ICP before/after test<br>**Solution**<br>• Acidity, alkalinity<br>• Sulphate<br>• Conductivity<br>• Dissolved metals,<br>• Radionuclides | **Solids**<br>• ICP before/after test<br>**Solution**<br>• Acidity, alkalinity<br>• Sulphate<br>• Conductivity<br>• Dissolved metals,<br>• Radionuclides | **Solids**<br>• ICP before/after test<br>**Solution**<br>• Acidity, alkalinity<br>• Sulphate<br>• Conductivity<br>• Dissolved metals,<br>• Radionuclides |
| Optional Analyses | • Sulphur Species | • Organics | • Mineralogy of solids<br>• ABA before/after test | • Mineralogy of solids<br>• ABA before/after test | • Mineralogy of solids<br>• ABA before/after test |
| Variations to Test Procedure | • Hydrogen peroxide oxidizable sulphur | • ASTM 03987<br>• B.C. Swep<br>• US EPA 1312<br>• US EPA TCLP<br>• Conduct test on uncrushed (as-received) sample | • Inoculation with bacteria | • Wet/dry cycles<br>• Flushing rate<br>• Single pass or recirculation of water through the sample<br>• Inoculation with bacteria<br>• Cells in series | • Wet/dry cycles<br>• Flushing rate<br>• Single pass or recirculation of water through the sample<br>• Inoculation with bacteria<br>• Columns in series |
| Particle Size | -.3 mm | Depends on test typically -0.6 | -0.6 cm | -10 cm | 2 to 50 cm |
| Amount of Sample required (kg) | 0.002 to 0.500 | 0.1 to 2.0 | 1 to 5 | 25 to 40 | 30 to 50 |
| Cost per Test[1] | $75 to $150 | $175 | $3000 | $4000 | $5000 |
| Time to Complete Test | 2 days | 2 days | 3-6 months | 3-6 months | 6-36 months |
| Certainty in Results | • Very good<br>• Static test only | • Indicative of leachable contaminants but not of field behaviour | • Indicative of ARD potential but not of field behaviour for mine rock | • Good | • Good |

Notes: 1) Laboratory Costs only
2) Depends on number of samples submitted
3) 10 week testing period ($90/each additional week)
4) 26 week testing period ($105/each additional week)
5) ICP, or selected metals by AA and less frequent ICP analysis of the dissolved metals.

This information is usually also presented graphically as a function of time or cycle number to indicate trends and rates of production. Care must be taken in evaluating the initial flushing cycles when the sample contains stored oxidation products or a readily soluble load, where there has been sample pre-treatment, or if control measures are being evaluated (eg. water cover, alkali addition), as these early cycles may reflect the flushing out of stored products and not long term trends in acid generation and contaminant leaching.

Figure 5.7 shows examples of "typical" curves for the different sources of contaminants. These are key to the interpretation of kinetic test results, as the test procedures are the same for evaluation of drainage water quality for both metal leaching and ARD. A similar pattern would be evident in rock pile drainage water monitoring. Typically, for metal leaching there would be:

- a high initial flush of contaminants within the first 2 to 5 pore volume replacements;
- a decreasing load with time, the period of which varies with the metal content, flush rate and solubility; and,
- a longer period of elevated metals in a trickle leach column as compared to a higher flushing rate (eg. a pore volume on a daily or weekly basis).

For ARD there would be:

- gradually increasing sulphate and acidity values with associated decreasing alkalinity;
- gradually increasing iron levels and decreasing pH lagging somewhat behind the sulphate peaks; and then,
- increasing dissolved metals in the drainage.

It is expected for most sites that the drainage water quality will be controlled by both mechanisms. The extent to which one or the other dominates will depend on the nature of the rock and the time period.

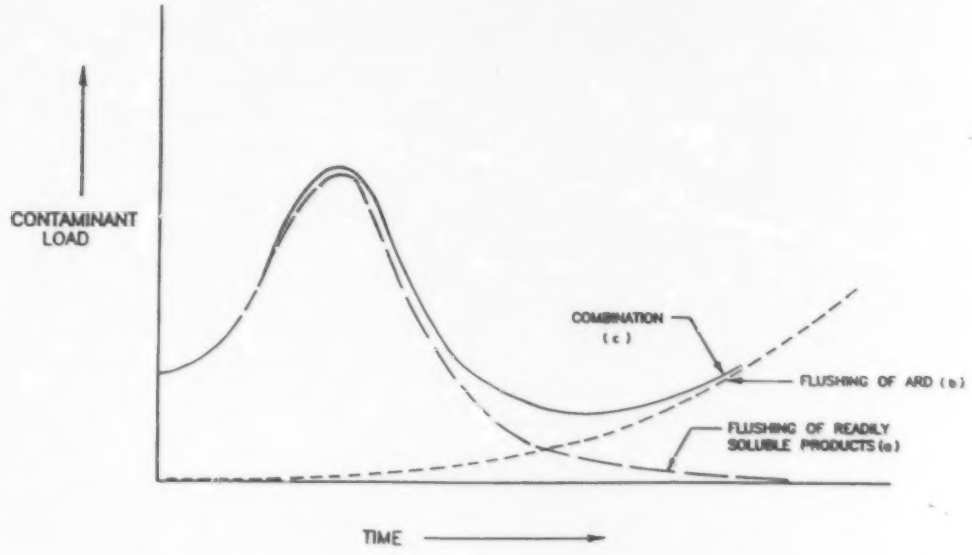



Figure 5.7 Typical Profiles of Drainage Water Contaminant Loading Over Time

Prediction of the long-term acid generating potential of a sample and potential water quality issues from interpretation of the results of the humidity cell testing can be complicated, and requires some experience in ARD testing. A discussion of the interpretation of results of kinetic testing is provided in the Draft Technical Guide, and forms the basis for the following general guidelines in interpreting test data.

**pH** > 5.0 sample is not strongly acid generating and/or the chemistry is dominated by release of alkalinity from calcareous material, during the testing period.

3.0 to 5.0 sample is generating acid although some pH neutralization is occurring. Biological oxidation becomes more significant (iron oxidizing bacteria).

< 3.0 sample is strongly acid generating and the role of *Thiobacillus ferrooxidans* can be significant.

**Sulphate** Sulphate is a direct by-product of complete sulphide oxidation, and can be indicative of the rate of sulphide oxidation and acid generation. Depending on the test procedure, there are a number of factors that must be incorporated in the interpretations: that all of the oxidized sulphur is flushed from the sample, and that solubility constraints do not result in precipitation of gypsum or other sulphate salts. Elevated sulphate analyses may indicate the presence of strong acid generation although the pH is neutral due to release of alkalinity from carbonate minerals. An increase in sulphate concentrations and the rate of sulphate production over the test period would indicate that the rate of acid generation was increasing. Release of sulphate in the initial weeks of testing may indicate only the dissolution of sulphate salts or release of stored oxidation products.

**Acidity** Acidity is a cumulative measure of several aqueous species such as $Fe^{2+}$, $Fe(OH)^{2+}$, $Al^{3+}$, and $HSO_4^-$. Thus, acidity can be used as a rough approximation of acid generation. The change in acidity/alkalinity and release of elements such as calcium and magnesium associated with alkali minerals is indicative of the rate and extent of acid generation and neutralization reactions. A correlation between sulphate and acidity frequently exists unless there is significant neutralization of the drainage.

**Metals** Analyses of dissolved metals will indicate the rate of metal depletion from the sample, by comparison with the original metal content of the sample. An increase in dissolved metals does indicate that either flushing of readily soluble products or acid generation and metal mobilization is occurring in the cell; however, it is not a good indicator of the rate of acid generation due to secondary effects such as hydrolysis and precipitation of secondary minerals.

In summary, the evaluation of data should include:

- Check for inconsistencies or errors; however, unusual values should be reviewed to determine if they are analytical errors or indication of change in the water quality;
- Plotting of changes in key indicator parameters over time; pH, sulphate, alkalinity, acidity. Changes in sulphate and alkalinity can indicate the onset of oxidation before changes in pH are apparent.

- Plotting of cumulative sulphate and acidity production and alkalinity consumption with time;
- Plotting of metals as a function of time and of pH;
- Plotting of contaminant production per unit time and unit surface area;
- Plotting of geochemical ratios of parameters such as sulphate, alkalinity, calcium, magnesium with time, particularly for samples with near neutral pH;
- Review of mine rock classification and ABA results;
- Comparison with other data from the site, and from other sites.

Evaluation of data should continue throughout testing, to determine if the results are useful and if changes should be made to the schedule of sample analysis, or if the tests can be concluded. As soon as the tests indicate that the material does generate unacceptable drainage water, the focus of the prediction program should change to the evaluation of control measures. Typically, kinetic tests are required to run for twenty weeks or more before analysis indicate final steady state conditions. Testing is often terminated if:

- pH becomes acidic (< 5) indicating acid generation is occurring (but final water quality is not of interest); and
- after 20 weeks, if pH is neutral or alkaline and NP/AP > 1.0 and there are no indications of increased sulphate production.

Tests should be continued as long as the data indicates that there are changes in water quality that indicate that the leaching or oxidation processes are developing or being depleted. Testing should continue:

- if pH is decreasing;
- if constant or increasing sulphate production;
- if increasing leachate metal concentrations; or,
- if test critical to control plan or can be modified to evaluate ARD controls.

# 6.0 CONTROL TECHNOLOGY

## 6.1 Introduction

The objective of control technology for mine rock piles is to prevent contaminated or potentially contaminated drainage water from adversely affecting the water quality of the downstream receiving environment. As discussed in Section 3, contaminants can be released by leaching of metals under oxidation and acid generation as well as by flushing and leaching of readily soluble metals under neutral or near neutral pH conditions. The techniques appropriate for controlling contaminant release at each site depend to some degree on the mechanism of release and the stage of mining at which the problem is identified.

There are three approaches to the control of ARD:

- control of the oxidation and acid generation processes;
- control of contaminant migration; and,
- collection and treatment of contaminated drainage.

The second and third apply also to contaminant migration from non-acid generating, but contaminant leaching, mine rock. The preferred approach for ARD control is to prevent the oxidation and acid generation reactions, either by eliminating one or more of the essential components (reactive sulphide mineral, oxygen, or water), or by controlling the environment to retard the rate of acid generation to an insignificant level. If the acid generation process is controlled, there is no risk of release of contaminants, and consequently the other approaches to control are not necessary. Where the oxidation reactions cannot be, or have not been prevented, contaminant migration should be prevented. If neither of these control measures have been implemented or if they have not been successful in meeting downstream water quality objectives, the contaminated drainage must be intercepted, collected and treated. Clearly, the least risk of environmental impact exists if the contaminants are never generated. The greatest risk and long-term liability results when there is a continuous and long-term need to operate and maintain collection and treatment systems. A combination of control measures may be the most effective and efficient approach.

For many existing mines, the potential for ARD and contaminant release was not identified during the design and operation of the mine rock piles, and control measures were not implemented.

The suitability and effectiveness of any control measure is dependent on a number of site specific conditions:

- type and physical characteristic of the mine rock;
- acid producing and neutralizing potential of the mine rock;
- site criteria such as climate, topography, surface and groundwater hydrology;
- time period for which the control measure is required to be effective; and,
- sensitivity of the receiving environment to ARD.

A recommended procedure for evaluating ARD control, which addresses the approaches to control in the order of preference discussed above, is presented as a flow-chart in Figure 6.1. Table 6.1 summarizes the applicability of each of the three approaches to both ARD and metal leaching control and the approaches are discussed in more detail in the sections below.

**TABLE 6.1**
**Summary of Approaches for Control of Acid Generation and/or Metal Leaching**

| APPROACH | METAL LEACHING | ACID GENERATION |
|---|---|---|
| Control of Oxidation and Acid Generation Reactions | No | Yes |
| Control of Contaminant Migration | Yes | Yes |
| Collection and Treatment of Contaminated Drainage | Yes | Yes |

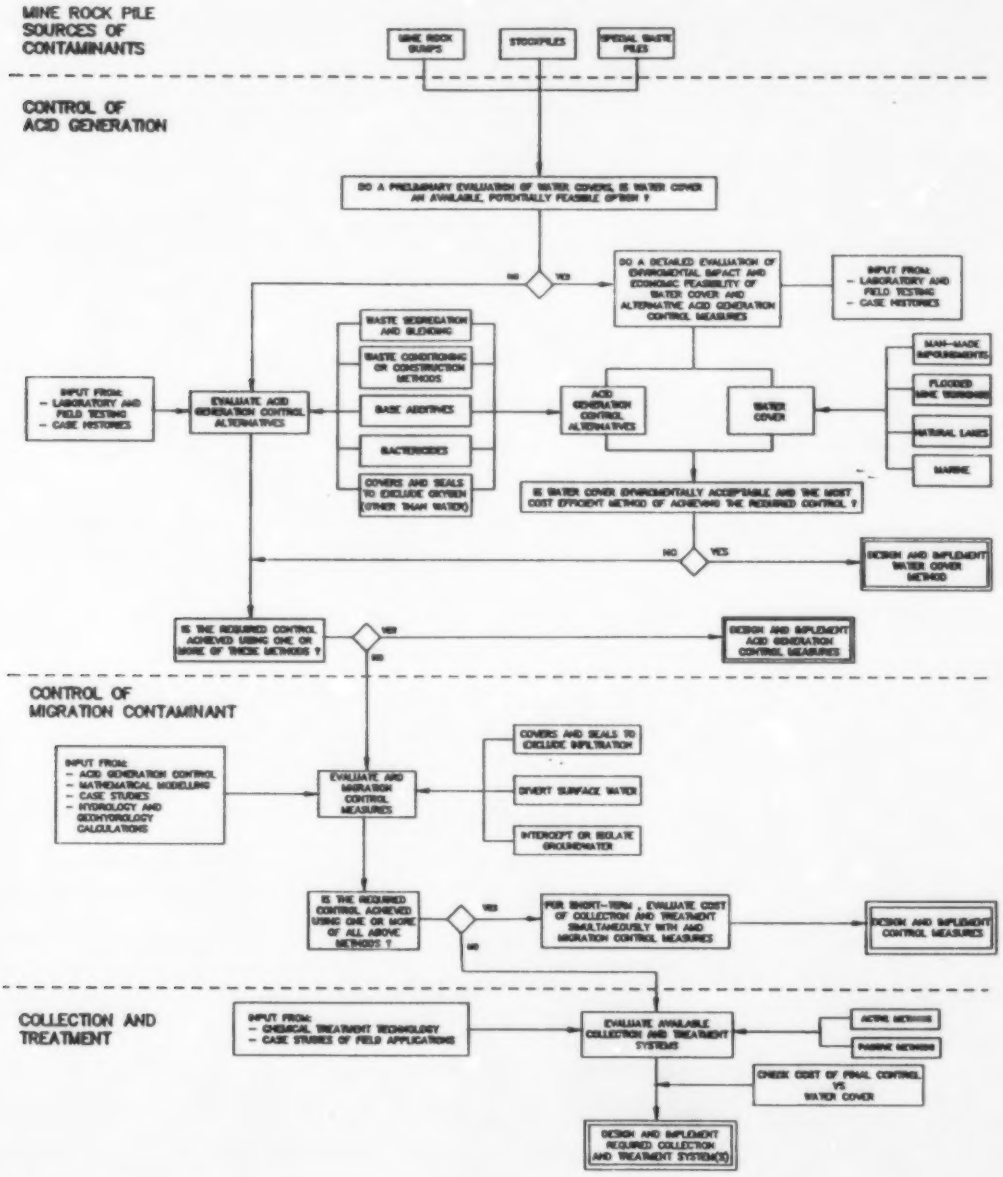

MINE ROCK PILE SOURCES OF CONTAMINANTS
MINE ROCK DUMPS
STOCKPILES
SPECIAL WASTE PILES
CONTROL OF ACID GENERATION
DO A PRELIMINARY EVALUATION OF WATER COVERS, IS WATER COVER AN AVAILABLE, POTENTIALLY FEASIBLE OPTION ?
NO
YES
DO A DETAILED EVALUATION OF ENVIRONMENTAL IMPACT AND ECONOMIC FEASIBILITY OF WATER COVER AND ALTERNATIVE ACID GENERATION CONTROL MEASURES
INPUT FROM: - LABORATORY AND FIELD TESTING - CASE HISTORIES
INPUT FROM: - LABORATORY AND FIELD TESTING - CASE HISTORIES
EVALUATE ACID GENERATION CONTROL ALTERNATIVES
WASTE SEGREGATION AND BLENDING
WASTE CONDITIONING OR CONSTRUCTION METHODS
BASIC ADDITIVES
BACTERICIDES
COVERS AND SEALS TO EXCLUDE OXYGEN (OTHER THAN WATER)
ACID GENERATION CONTROL ALTERNATIVES
WATER COVER
MAN-MADE IMPOUNDMENTS
FLOODED MINE WORKINGS
NATURAL LAKES
MARINE
IS WATER COVER ENVIRONMENTALLY ACCEPTABLE AND THE MOST COST EFFICIENT METHOD OF ACHIEVING THE REQUIRED CONTROL ?
NO
YES
DESIGN AND IMPLEMENT WATER COVER METHOD
IS THE REQUIRED CONTROL ACHIEVED USING ONE OR MORE OF THESE METHODS ?
YES
NO
DESIGN AND IMPLEMENT ACID GENERATION CONTROL MEASURES
CONTROL OF MIGRATION CONTAMINANT
INPUT FROM: - ACID GENERATION CONTROL - MATHEMATICAL MODELLING - CASE STUDIES - HYDROLOGY AND GEOHYDROLOGY CALCULATIONS
EVALUATE ANY MIGRATION CONTROL MEASURES
COVERS AND SEALS TO EXCLUDE INFILTRATION
DIVERT SURFACE WATER
INTERCEPT OR ISOLATE GROUNDWATER
IS THE REQUIRED CONTROL ACHIEVED USING ONE OR MORE OF ALL ABOVE METHODS ?
YES
NO
FOR SHORT-TERM , EVALUATE COST OF COLLECTION AND TREATMENT SIMULTANEOUSLY WITH ANY MIGRATION CONTROL MEASURES
DESIGN AND IMPLEMENT CONTROL MEASURES
COLLECTION AND TREATMENT
INPUT FROM: - CHEMICAL TREATMENT TECHNOLOGY - CASE STUDIES OF FIELD APPLICATIONS
EVALUATE AVAILABLE COLLECTION AND TREATMENT SYSTEMS
ACTIVE METHODS
PASSIVE METHODS
CHECK COST OF FINAL CONTROL VS. WATER COVER
DESIGN AND IMPLEMENT REQUIRED COLLECTION AND TREATMENT SYSTEM(S)

Figure 6.1 Flow Chart Showing Approach to Evaluation and Selection of Control Technology

The first step in controlling acid generation is to identify all potential sources through a site investigation and prediction program. Appropriate sampling, testing and prediction methods have been summarized in Sections 4 and 5.

## 6.2 Control of Oxidation and Acid Generation Processes

### 6.2.1 General

The objective of acid generation control is to prevent or reduce the formation of acid at the source by inhibiting sulphide oxidation. Prevention of the acid generation reactions is the most preferable form of control and, if possible, should be the primary long-term approach. At existing facilities where oxidation and acid generation are currently occurring, these control techniques could be used to stop or reduce the rate of future acid generation; however, because acid products have already been stored, these control measures should be implemented in conjunction with measures to control migration and, if necessary, to collect and treat existing contaminated drainage. Table 6.2 highlights the control measures for acid generation in terms of the process that they are intended to prevent or reduce. The control measures are briefly summarized below. More details can be obtained from the references provided in Table 6.2 or from the Draft Acid Rock Drainage Technical Guide (SRK et al, 1989).

### 6.2.2 Conditioning of Mine Rock

The objective of conditioning mine rock is to reduce the sulphide content by removal or by rendering chemically stable and consequently, reduce the acid potential. For mine rock, removal would involve additional crushing to facilitate flotation separation and would produce a sulphide concentrate and flotation tailings. The flotation tailings may still have some acid potential but it would be less than the original mine rock. However, the sulphide concentrate would require special disposal for control of ARD potential. In general, reprocessing of mine rock is not efficient or cost effective; however, for new mines or mines that are considering (re)processing mine rock for mineral recovery other than uranium, additional processing for sulphide removal should be considered.

**TABLE 6.2**
**Summary of Available Acid Generation Control Measures**

| CONTROL OBJECTIVE | CONTROL MEASURE | METAL LEACHING | ACID ROCK DRAINAGE |
|---|---|---|---|
| Remove or Isolate Reactive Sulphide | Conditioning of Mine Rock | YES | YES |
| Exclude Water | Covers and Seals | NO | YES |
| Exclude Oxygen | Underwater Deposition | NO | YES |
| | Covers and Seals | NO | YES |
| Control pH | Mine Rock Segregation & Blending | NO | YES |
| | Base Additives | YES | YES |
| Control Bacterial Action | Bactericides | NO | YES |
| | Temperature | NO | YES |

The conditioning of exposed sulphides to render them chemically inert by applying a phosphate compound has shown promise for tailings treatment. It may be applicable to durable mine rock where weathering and slaking will not expose untreated surfaces, provided all mine rock can be thoroughly coated. Thorough coating would require spraying or mixing prior to placement in the pile since applications to the pile surface results in only partial coating at depth. While such chemical isolation holds promise it is at this stage still experimental and the long term effectiveness is questionable.

### 6.2.3 Covers and Seals

Covers and seals, which are placed as a layer on top and sides of a reactive mine rock pile, can be used to restrict the access of oxygen and water and thus, inhibit acid generation. To limit oxygen or water entry, the cover must have a low permeability to either air or water and it must be sufficiently free of holes or imperfections through which entry can occur.

The exclusion of water to the extent that acid generation does not occur is not considered practical (Robertson, 1987), except in very arid climates, however covers and seals help to inhibit subsequent contaminant migration. Table 6.3 summarizes several alternative cover materials (Nolan, Davis and Associates, 1987) as well as their typical permeability to water. The use of covers and seals for controlling contaminant migration will be discussed in Section 6.3.

The exclusion of oxygen must allow for all the oxygen transport mechanisms:

- convection due to temperature differences between air in the pile and the outside air;
- advection caused by barometric pumping as a result of barometric pressure changes and as a result of wind pressures and suctions caused by airflow over the pile; and,
- diffusive flow into the pile.

One of the concerns associated with covers and seals is the long term effectiveness which is related to the resistance of the cover to cracking, the burrowing effects of roots and animals, erosion and degradation due to weathering and frost action. These actions serve to increase the permeability of the cover by producing holes in the cover or by modifying the soil structure.

Water is currently considered to be the most effective cover for excluding oxygen while the other materials are better suited to controlling infiltration and hence, contaminant migration. With underwater disposal the interstices of the mine rock are filled with water thus the potential for air movement by advective and convective pressures is eliminated, though there is still the potential for dissolved oxygen to be transported in water flowing through the interstices. Water cover (underwater disposal or a saturated soil/bog cover) for preventing acid generation should be evaluated for any control plan however the establishment of a water cover on an existing rock pile is not practical in most cases. Water covers are discussed in conjunction with underwater disposal in the next section. Covers combining water with alternative materials which establish a perched water table or surface saturated layer may also be effective. More details on the different types of covers and seals can be obtained from the Draft Acid Rock Drainage Technical Guide (SRK et al., 1989).

**TABLE 6.3**
**Alternative Cover Materials**
**(After Nolan, Davis and Associates, 1987)**

| COVER MATERIAL | PERMEABILITY TO WATER (m/sec.) | ADVANTAGES/DISADVANTAGES |
|---|---|---|
| Compacted Clay | $10^{-9}$ to $10^{-11}$ | Availability of large quantities problematic in many areas. Subject to erosion, cracking and root penetration. Good sealing if protected and maintained. |
| Compacted Till | $10^{-7}$ to $10^{-9}$ | As above but generally more permeable. |
| Compacted Topsoil | $10^{-5}$ to $10^{-8}$ | As above but less robust, more permeable. Questionable longevity. |
| Peatland Bog | $10^{-5}$ to $10^{-6}$ | Need to maintain in saturated condition. Normally impractical for elevated mine rock piles and side slopes. |
| Concrete | $10^{-10}$ to $10^{-12}$ | Subject to cracking, frost and mechanical damage. |
| Asphalt | $10^{-20}$ | As above. |
| HDPE Synthetic | Impermeable | Requires proper bedding and protective cover. Highly impermeable. Lifespan unlikely to exceed 100 years. Subject to mechanical penetration. |

### 6.2.4 Underwater Disposal

Underwater disposal is currently the most promising acid generation control measure. The objective of placing potentially acid generating mine rock under water is to exclude oxygen; the diffusion rate of oxygen through water is very low. Thus, in the absence of convective transport, the rate of oxygen transport through water is sufficiently slow that the acid generation reactions can be effectively limited to make the impact negligible. However, the short term release of readily soluble contaminants such as uranium, arsenic and nickel will

be accelerated by flooding, and the potential for migration of these contaminants becomes a concern.

The effectiveness of underwater disposal in controlling oxidation, acid generation and metals release from mine rock has been observed at the Skorovas Mine in Norway (Liseth and Miljøplan, 1991) and at the Island Copper Mine in Canada. Canmet-MEND (1989) describes several case histories and public documents which indicate positive results for underwater disposal of tailings. There is steadily accumulating evidence that underwater disposal of potentially reactive mine rock reduces acid generation to negligible levels (Nolan, Davis and Associates, 1987; Robertson, 1987; McCready, 1987; Senes Consultants Ltd., 1984; City Resources Inc., 1988; SRK, 1988(b)).

To prevent the initiation of the oxidation and acid generation reactions, an adequate water cover must be permanently maintained over the reactive mine rock. In general, the oxygen flux and oxygen concentration at the solid/water interface can be limited with a nominal depth of standing water. However, the depth of the water above the mine rock must take into account the effects of seasonal water level fluctuations, wave action, convection and seasonal lake overturn that may increase the flux of oxygenated water to the solids, or disturb the solid surface and release fines into the overlying water column. Increasing the depth of water and placing a layer of innocuous, coarse rock on the mine rock surface can provide control of oxygenated water movement to and through the mine rock.

In Saskatchewan, there are three potential areas for underwater disposal of mine rock:

- deposition or relocation in flooded mine workings;
- man-made impoundments; and,
- natural lakes.

Mine rock can be relocated or deposited in open pits and, to a lesser degree underground workings, which can then be flooded to control acid generation from both the exposed rock faces in the mine walls as well as infilled mine rock. When flooding existing mines there is potential for releasing stored loads of soluble oxidation products.

The release of soluble contaminants to the overlying waterbody can be reduced and possibly controlled by techniques such as:

- placement of a till cover over the mine rock prior to flooding to provide chemical attenuation of contaminants, and limit flow through the mine rock; or,
- layering of mine rock with alkali, such as lime or finely crushed limestone.

In northern Saskatchewan, the regional water table has generally been very high since the last glaciation period and as a result, dewatering for mining is responsible for the first introduction of oxygen into the surrounding rock through the porosity of the rock:

- primary porosity occurs within the rock material and varies from 0% for the basement rock to 10 to 15 % for the Athabasca sandstone;
- secondary porosity depends on the type, spacing and continuity of discontinuities such as joints and faults within the rock mass. Barometric pumping of air into the partially saturated rock mass above the water table continues to promote oxidation before drilling, blasting and excavation and leads to material having leached products available for immediate release. If there are large amounts of stored products, some form of pH control may be required when mine rock is placed under water.

A man-made structure, constructed as a water retaining structure, could be used for underwater disposal of mine rock (and tailings). The practicality and cost of a man-made reservoir relative to alternative measures is clearly dependent on site specific conditions. Generally, this type of structure would include low permeability embankments, possibly a base liner, as well as spillway facilities, and would require detailed engineering design, construction control and long-term maintenance.

Lakes have been used in the past for the disposal of both potentially acid generating and non-acid generating tailings:

- Westmin Mine near Buttle Lake, B.C. (Pedersen, 1983);
- Surf Inlet Mine near Bear Lake (Errington and Ferguson, 1987);

- Mandy Mine near Mandy Lake, Manitoba (Hamilton and Fraser, 1978);
- a copper mine near Benson Lake, B.C. (Hallam et al., 1974); and,
- Bluebell Mine near Kootenay Lake, B.C. (Daly et al., 1981).

The results from research at these sites suggests that acid generation from the tailings has had no major long term impact on lake water quality (Canmet-MEND, 1989). Available evidence indicates that the deposition of acid-generating rock underwater, such as into a lake, will effectively control the rate of acid-generation. However, turbidity and release of readily soluble metals, which may affect the biological communities in the lake, must be evaluated for the lake disposal option (Arnesen et al., 1988).

The selection of the most appropriate option for underwater disposal or water cover will depend on a number of site specific factors:

- nature and quantity of mine rock;
- site topography and existing water bodies;
- land and lake use and reclamation objectives;
- site hydrology; and,
- regulatory requirements and public acceptance.

Since natural lakes are abundant in Saskatchewan, there is often potential for using an existing lake for disposal. Many of the ore bodies in northern Saskatchewan are located in low-lying areas or former lakes and swamps. After mining and dewatering is terminated the natural water table will recover. Construction of rock piles in these low-lying area may provide a natural water cover after closure. The extent to which generation and storage of soluble products will develop during operation must be addressed in the design of the control measures. It has been demonstrated that a viable ecology can be created above mine rock placed underwater. However, proposals to dispose of mine residues, such as mine rock or tailings, into natural water bodies are often opposed by regulatory agencies and the public for environmental and political reasons. The cost of on-land disposal under a water cover in man-made impoundments, relative to lake disposal, and the environmental implications associated with each should be considered.

### 6.2.5 Mine Rock Segregation and Blending

Mine rock segregation involves the careful removal and separate handling of various mine rock units at a minesite according to their ARD classification and different control requirements. The segregation and separate handling of acid-generating and acid-consuming rock classes, can minimize the total volume of material which has to be controlled as well as provide the potential for blending of the materials to give a similar effect as base addition. Segregation may be appropriate if there is a low volume of highly acid generating or leachable rock. The objective of blending is to increase the ratio of acid consuming to acid generating rock, particularly for marginally acid generating rock.

The success of blending as control of acid generation depends primarily on the grainsize and intimate mixing of the rock types, the movement of water through the system, the nature of contact of acidic rock or water with neutralizing additives or water, and the proportion of excess neutral material, and the type and purity of neutralizing additive. Extensive laboratory simulation is usually required to demonstrate the effectiveness of blending and additional supplementary control measures may be required. Blending has been successfully used in the coal mining industry of the Eastern USA.

### 6.2.6 Base Additives

The potential for acid generation is based on the relative proportions of acid-producing and acid-consuming materials. Excess basic or neutralizing material, such as limestone, lime and sodium hydroxide, can be layered within the acid generating mine rock during placement or mixed after placement.

As with blending, the success of base additives to control acid generation depends primarily on the degree of mixing, the movement of water through the system, the nature of contact of acidic rock or water with neutralizing additives or water, the proportion of excess neutral material and the type and purity of neutralizing additive. In general, intimate mixing is required, or very thin layers, to ensure close proximity of alkali material to the acid generating reaction sites. Surface applications have decreasing effects with depth due to selective channelling of inflow water and consumption of the finite dissolved load of alkali.

Base additives, such as finely ground limestone that is intimately blended with the mine rock, may be suitable in the long term, depending on the quantity, type and reactivity of the sulphide minerals. Blending of mine rock is a form of base addition in which rock with surplus alkalinity is blended with the acid generating mine rock. The adequate blending of alkaline materials with coarse hard rock waste may require crushing and intimate blending and adequate appropriate laboratory or field trials would also be required to demonstrate its effectiveness.

### 6.2.7 Bactericides

As discussed in Section 3, the rate of sulphide oxidation and acid generation is enhanced in most natural mine rock environments by microbiologic activity, particularly that of *Thiobacillus ferrooxidans*. Bactericides can be used to create a toxic environment for bacteria so that the inorganic rate of acid generation can not be enhanced. Bactericides, which can be easily applied to surfaces of mine rock piles as a liquid using sprayers and hydroseeders, become less effective with depth where distribution becomes poor due to selective flow channelling. Uniform penetration is more successful for fine grained materials such as tailings and slaking coal wastes. Effectiveness decreases with depth and has only moderate effect in hard rock wastes at a depth of a few feet. Bactericides degrade and have a limited life, and liquid applications must be repeated at intervals of a few months. In rubberized pellet form the bactericide is released slowly and, if mixed with the waste when the waste is placed, may be effective for a few years. Bactericides control only the biological oxidation processes and not chemical oxidation of sulphides. Based on laboratory and field studies, bactericides may reduce the rate of acid generation in metal mining for limited periods, but will not eliminate ARD. Consequently, bactericides might be a suitable short-term acid generation control measure but must be used in conjunction with other control techniques, particulary for long term control.

### 6.2.8 Temperature

As discussed in Section 3, both chemical and biological reactions of acid generation are temperature dependent. The bacteria become dormant and the transport water will freeze at temperatures below zero. Experience in Russia and at the Faro mine, Yukon, indicates that

a coarse rock cover acts as a cold trap. Since temperatures in northern Saskatchewan are below 0°C for several months each year, there is potential for inducing reduced temperatures into the pile by artificial means.

As a general rule, the rate of reaction is halved for every 10°C decrease in temperature.

## 6.3 Control of Migration

Where acid generation is not prevented, the next approach to control is to prevent or reduce the migration of leachable products to the environment. Contaminants can be transported as a result of surface water or groundwater flushing. Since the long-term flow attenuation in a mine rock pile is negligible, all water entering the mine rock must exit in the long term; consequently, to minimize the quantity of contaminated seepage, the control of migration relies on preventing water entry. Control of the migration of contaminants is an area in which considerable development has been achieved in recent years. The measures which may be necessary for controlling contaminant migration are summarized in Table 6.4.

The methods of control of contaminant migration are sensitive to both the nature of the site and the duration for which control is required. Consideration of all site parameters is critical to selecting the optimum control measures or combination of measures.

**TABLE 6.4**
**Summary of Measures for Contaminant Migration Control**

| CONTROL MEASURES | METAL LEACHING | ACID ROCK DRAINAGE |
|---|---|---|
| Diversion of surface water. | Yes | Yes |
| Interception of groundwater. | Yes | Yes |
| Covers & seals to reduce infiltration. | Yes | Yes |
| Controlled placement to reduce infiltration. | Yes | Yes |

*Diversion of Surface Water*

Surface water can be diverted from a mine rock pile using ditches, berms and surface contouring. Diversion of surface flows, while easily implemented, is often difficult to maintain in the long term without maintenance. For the long term, appropriate site selection to avoid natural drainage channels and to minimize contact with surface water runoff is the most cost effective design measure. Favourable sites for minimizing surface water runoff are at the crest of slopes or on small plateaus and near to the upstream end of a watershed; however, there may be unfavourable cost implications based on distance from, or location in relation to the mine. If necessary, ditches, berms and other structures may be used in the long term, although a certain level of ongoing inspection and maintenance will be required.

*Interception of Groundwater*

Groundwater flow into mine rock piles can best be prevented by site selection to avoid groundwater discharge areas. Where rock piles are located on groundwater discharge areas the groundwater interception or isolation under mine rock piles will generally be difficult to implement and maintain. Lateral flow of groundwater towards a rock pile may be cut-off or intercepted with slurry walls, grout curtains, deep drainage ditches and boreholes or wells. Interception of groundwater by means of gravel filled ditches, wells and pumps may be suitable in the short term only because of the need for on-going maintenance and replacement. Salt precipitation (particularly iron salts in ARD) can rapidly blind off drainage layers, rendering them ineffective. Impermeable cut-off walls may be more suitable in the longer term.

*Reduction of Infiltration*

The principle source of transport water for contaminant migration from a mine rock pile is usually infiltration of precipitation; therefore, infiltration control is essential for controlling contaminant migration. Low permeability covers and seals are the most practical method of controlling infiltration of precipitation and can range from simple soil covers such as compacted till, through composite covers consisting of two or more layers of soil with different permeabilities, to synthetic covers and water covers. The materials and complexity

of a cover must be balanced against the reduction of water flux that is needed and the duration over which control is required.

i) Simple soil covers

Simple covers are constructed from a single layer of soil and can be installed for about $2 to $6/m$^2$. A fine grained soil, such as a clay, silt or till, can be used to reduce infiltration.

Infiltration rates can be estimated using the HELP (Schroeder et al., 1984) model or TRUST (Reisenauer et al., 1982) codes. In a slow thawing environment, much of the annual infiltration occurs during the period of snow melt and simple soil covers seldom reduce infiltration below 5 to 10 percent of precipitation.

A high moisture content is required to limit oxygen transport through a cover. For unsaturated soil covers, the typical reduction in oxygen flux due to diffusion is illustrated in Figure 6.2 determined using the RATAP model, (Senes and Beak, 1988). This shows that oxygen entry by diffusion is reduced but is still substantial with up to a few metres of cover. When the moisture content is increased to saturation, water fills the void spaces in the soil and the ability to transfer oxygen is limited to the diffusion rate of oxygen through the pore water. For saturated soil, the oxygen flux may be in orders of magnitude lower than for partially saturated soils.

Simple covers are subject to desiccation cracking as a result of large seasonal variations in moisture content, which could result in increased permeability. In addition, the fine grained soils required to limit infiltration may be susceptible to frost damage, wind and water erosion, settlement, burrowing and root action which may also increase hydraulic conductivity and infiltration with time. Single layer soil covers may not reduce infiltration sufficiently to adequately reduce the contaminant load issuing from the rock pile.

ii) Complex covers

The effectiveness of a cover may be greatly improved by incorporating several layers with different characteristics. The design and composition of the cover determine the permeability

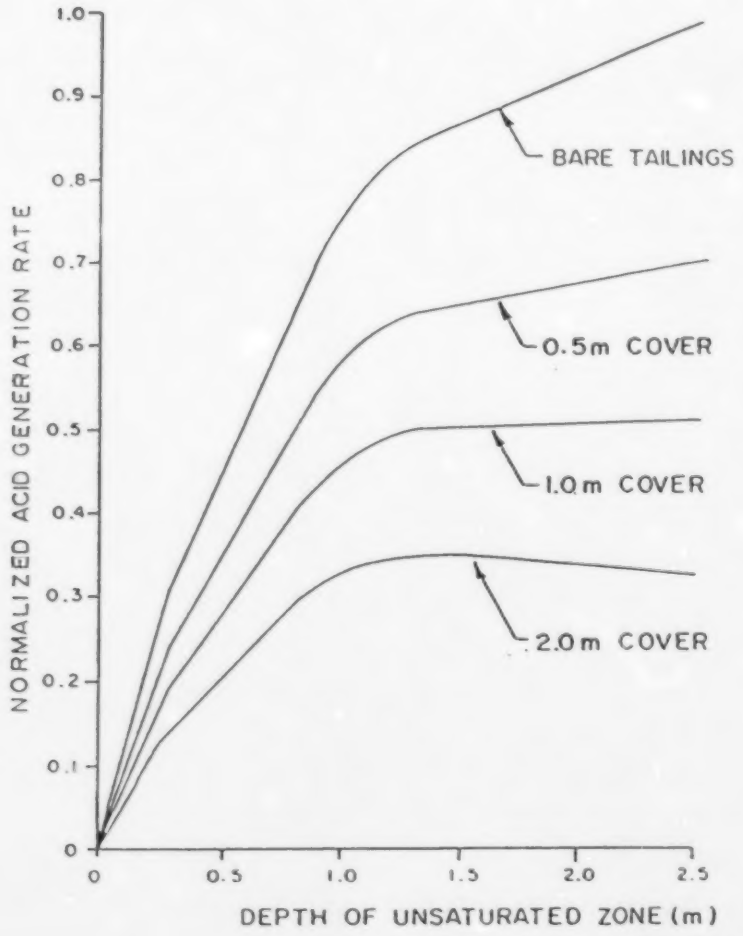



Figure 6.2 Effect of Till Cover Depth on Acid Generation Rate in Tailings (After SRK et al., 1987)

of the cover to water and to air, and the possible flux through to the underlying mine rock. Each layer is intended to perform a specific function to improve water and oxygen exclusion and long-term stability. As shown on Figure 6.3 a complex cover is typically made up of a combination of the following components:

- erosion control layer to protect the surface from wind and water erosion;
- moisture retention zone to limit desiccation of underlying layers;
- upper drainage or suction break layer to drain water from the infiltration layer and to prevent moisture loss from the infiltration barrier;
- infiltration barrier to prevent the downward infiltration of water and the diffusion of oxygen; and,
- lower capillary barrier to prevent desiccation of the infiltration barrier and to prevent suction of contaminated pore water up into the cover during dry periods.

The principals of complex cover design are discussed in Barton-Bridges and Robertson, 1989. Complex covers can be constructed with soils and/or synthetic materials or a combination of these. Figure 6.4 shows several alternative cover types as applied to tailings for Elliot Lake, Ontario conditions (SRK et al., 1987). The main components which affect the overall water balance of the cover are also presented. With no cover, almost all of the precipitation infiltrates a mine rock pile and would emerge as seepage. The results show considerable benefit of a complex cover design over a simple cover, and the additional benefit of adding a synthetic liner. An engineered cover with a synthetic membrane liner is by far the most effective infiltration barrier; however, the selection of an appropriate cover will depend on the conditions of the site and the level of control required.

Evaluation of alternative cover designs can be done using field tests plots and/or laboratory tests combined with computer models. The modelling of oxygen flux through a cover can be done with a model such as the KEMAKTA model (Colin et al., 1990) which calculates oxygen flux through a cover and oxidation rate in the underlying solids.

Two mines in Europe have constructed complex covers over acid generating mine rock to maintain a very low permeability layer for reducing oxygen entry and water flux to very low levels. Bersbo Mine in Sweden (Sodermark and Lundgren, 1988; Lindahl, 1990) have

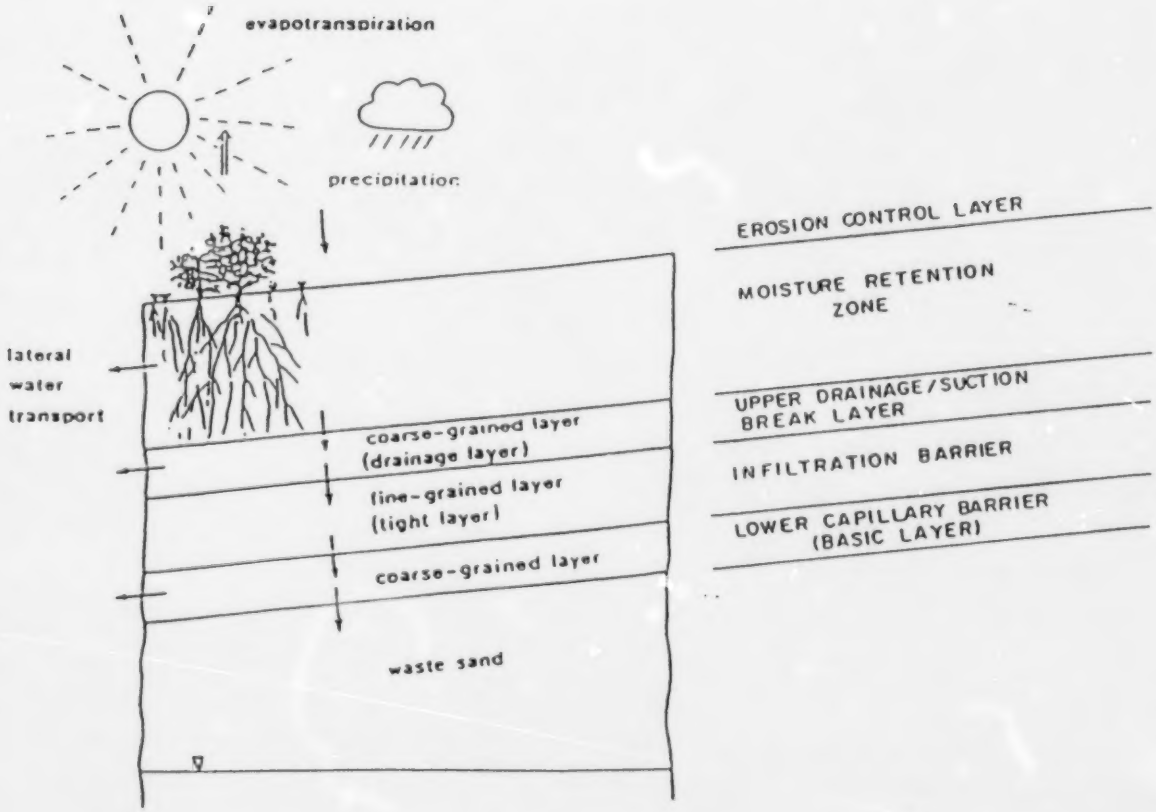
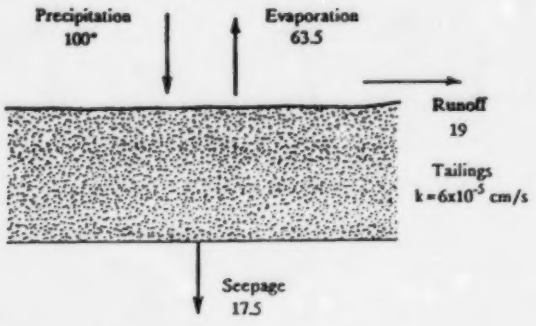
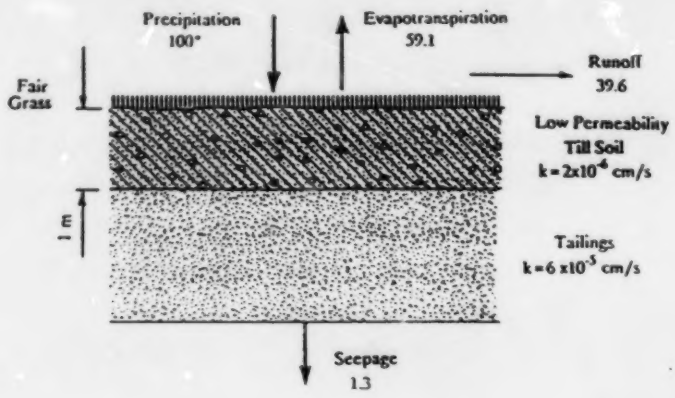


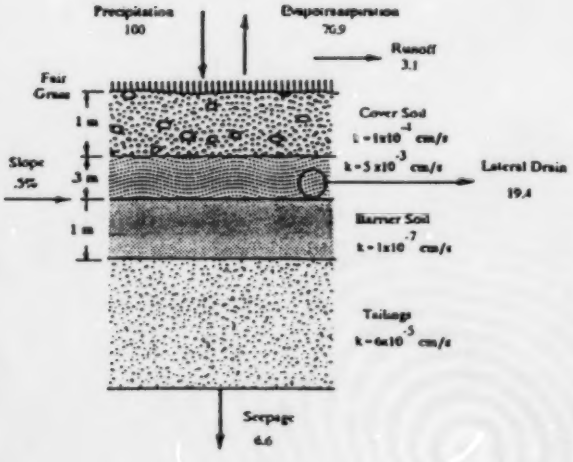

Figure 6.3 Typical Components of a Complex Cover (after Rasmusson and Eriksson, 1987)



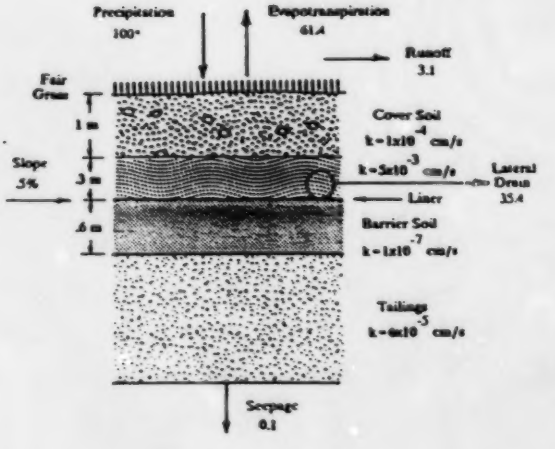

NO COVER




LOW PERMEABILITY TILL SOIL-COVER




SOIL BARRIER WITH LATERAL DRAIN AND SOIL COVER




SOIL BARRIER WITH SYNTHETIC MEMBRANE LINER, LATERAL DRAIN AND SOIL COVER

Figure 6.4 Alternative Cover Types Showing the Typical Percentage of Precipitation (After SRK et al., 1987)

incorporated clay and Cefyll (cement stabilized flyash) layers while the Kjøli Mine in Norway have installed a complex cover incorporating a 2 mm HDPE synthetic membrane. Costs of these complex multi-layered covers are generally in the range of $20 to $30/m$^2$.

The relative effectiveness of simple and complex soil covers in controlling migration may be obtained from mathematical model simulations of covers and from the monitoring of a limited number of actual covers. Although theoretical simulations are useful in comparing alternative cover types, their relative reliability is still in question and the true effectiveness of covers in controlling acid rock drainage has yet to be determined from monitoring the performance of actual covers in the field. Unfortunately, monitoring results are limited. The final measure of the effectiveness of the covers is reduction of metal loads in the local river system.

iii) Synthetic membrane covers

There are several synthetic covers which could be used including geomembranes, asphaltic and spray on seals, and geopolymers. Asphaltic and spray on surface sealants (asphalt, concrete, epoxy, polyester, polysulphide, silicone, synthetic rubber, etc.) can theoretically be applied to the surface of suitably smoothed and prepared mine rock to form a barrier to infiltration and oxygen diffusion. These materials have, in general, been developed for applications such as caulking sealants, soil stabilizers, water proof barriers, and corrosion coatings and their application to mine waste covers is as yet not demonstrated. Geopolymer is the term given to a compound of minerals, principally containing silica, phosphate and oxygen that bond to form a ceramic type product. The suitability of using this product as a control measure for acid generation is currently being investigated in Canada by CANMET. Shotcrete using a silicafume concrete and polypropylene fiber reinforcement to control cracking may be effective. The advantage of shotcrete is that it is a relatively inexpensive filler and can be applied as a cover to steep rock slopes or other surfaces which may be difficult to cover using other methods. The effective use of shotcrete as a cover is dependent on the stability of the underlying material.

The placement of covers on mine rock is complicated by the difficulties of the coarse texture of the surface and the access, trafficability and stability of the surfaces onto which the cover

is to be placed. These difficulties often render a particular cover type impractical or prohibitively expensive. Pile slopes are usually placed at their angle of repose and, as a result, are inaccessible, untrafficable and marginally stable. Cover placement on such steep slopes is essentially impractical and requires resloping to a slope of at least 3 horizontal to 1 vertical (3:1). The cost of resloping large mine rock piles is very large unless it had been planned for and the piles constructed with a staggered slope. The upper surface of a mine rock pile is usually readily accessible, trafficable and nearly flat. The placement of any type of surface cover, except a water cover, is usually not difficult. Rock piles are subject to long term consolidation and settlement under the self weight of the rock and as the rock weathers. These settlements are large and uneven, reflecting the natural variation of the mine rock pile and construction methods.

All types of covers require long-term monitoring and maintenance, though the amount may differ substantially between the different types.

*Placement of Mine Rock*

Methods of placing waste rock, spoil or tailings to minimize infiltration should be considered as part of planning waste management operations, in conjunction with other control methods.

Control of contaminant migration in mine rock piles can be assisted by engineered placement methods such as cellular dump construction, compacting, mixing with low permeability material, etc. Cellular dump construction, when used in conjunction with a cover layer, can significantly reduce the area of leaching mine rock exposed to precipitation.

Control of contaminant migration by compacting or mixing with low permeability material are intended to both reduce the bulk permeability of the mine rock pile and reduce infiltration. Compacting of mine rock will require construction in thin layers and is only suitable for soft rocks such as the Athabasca sandstone units common to several of the uranium deposits. This approach will also reduce settlement and increase dump stability. While these placement activities may have beneficial results, the extent of the benefit is often small compared to the incremental cost, and may not be justifiable except in very special circumstances.

## 6.4 Collection and Treatment

### 6.4.1 Introduction

The characteristics of contaminated runoff at uranium mines in Canada are very site specific. However, several contaminants are common, and the principal contaminants of concern are as follows:

- uranium;
- radium;
- arsenic;
- nickel;
- thorium; and,
- miscellaneous metals

In addition there are various soluble salts and metals, which are made soluble as a result of acid generation, following the natural oxidation of sulphide minerals.

Collection and treatment is considered as a the last approach for the control of ARD, and release of leachable contaminants, to the environment. To date collection and treatment has been the most widely applied ARD and contaminated runoff abatement method. Treatment measures that may be applied can be subdivided into two broad categories:

- active treatment systems; and,
- passive treatment systems.

Chemical treatment, such as lime neutralization, is typical of active treatment systems, where continuous operation and maintenance demands constant human interaction. Natural wetlands are typical of passive treatment systems, where, without the intervention of man, natural processes result in the amelioration of effluent water quality.

The alternative treatment systems are applicable to drainage contaminated by both ARD and readily soluble metals, and are summarized in Table 6.5.

**TABLE 6.5**
**Summary of Available Treatment Measures**

| COLLECTION AND TREATMENT OF CONTAMINATED DRAINAGE | METAL LEACHING | ACID ROCK DRAINAGE |
|---|---|---|
| ACTIVE TREATMENT<br>Chemical<br>· lime neutralization<br>· sorptive processes<br>Biological<br>· sulphate reduction<br>Physical<br>· solid/liquid separation | Yes | Yes |
| PASSIVE TREATMENT<br>Chemical<br>· alkali trenches<br>· attenuation along flowpath<br>Biological<br>· sulphate reduction<br>· wetlands<br>· metal uptake in plants<br>Physical<br>· physical removal - filtration by plants<br>· attenuation | Yes | Yes |

Each of these systems have their respective advantages and disadvantages. Frequently, potential treatment options are eliminated by virtue of site specific conditions. However, treatment systems are only as efficient as the collection system upon which they rely.

### 6.4.2 Collection Systems

Depending on the degree of contamination, collection of both surface and ground water may be required. Surface runoff collection may readily be achieved with surface ditching. The collection of subsurface flows may require the installation of collection trenches, wells within the contaminant plume, or cut-off walls to force groundwater flow to the surface where it can be collected and treated.

Design of collection systems are extremely site specific, and may depend on location of contaminated flow, topography, quantity and form of precipitation, and the geology and hydrology of the site. Collection systems invariably are made up of different components contributing to the efficiency of the overall collection system. These include the following:

- interception for freshwater diversion;
- contaminated flow collection; and,
- storage capacity.

Interception, to divert fresh water away from the catchment where the contaminants are being generated, is essential to minimise the volume of contaminated flow that may be generated from the site. The volume of flow to be treated will be minimised and thus the required design capacity for the water treatment alternative. In some instances certain benefits may be had by the additional dilution available when a diversion system is not implemented.

Design of both interception (diversion) and collection systems will depend on the peak instantaneous discharge from the catchments, with the design return periods depending on the assessed risk of discharge of a portion of the contaminated effluent.

Since it is unlikely that treatment plants will be designed to treat instantaneous peak discharges, a storage facility to regulate the flows to the treatment plant forms an integral part

of any collection system. Depending on a risk assessment, the storage capacity will be determined to hold the flood events up to a flood event with a specific return period.

The efficiency and overall performance of a collection system depends not only on appropriate design and construction methods but also on periodic inspection and maintenance to correct the many imperfections that develop as a consequence of erosion, sedimentation, glaciation, vegetation growth and disturbance by man and animals.

### 6.4.3 Active Treatment Systems

The objective for the treatment of ARD and contaminated runoff is:

- to neutralise acidity;
- to remove metal contaminants by precipitation as stable compounds or extraction by various methods; and,
- to remove any deleterious substances.

In addition to chemical neutralisation, treatment technologies such as sulphide precipitation, co-precipitation with various reagents, ion exchange and reverse osmosis may be used individually or in combination to achieve discharge objectives. In rare cases the metal content of the effluent may be sufficiently high to recover the metal economically, in which case hydrometallurgical processing options such as solvent extraction may also be considered as a viable treatment alternative.

*Acid Neutralization and Metal Hydroxide Precipitation*

Sulphuric acid in acidic rock drainage results from the natural oxidation of, for example, pyrite ($FeS_2$). Primarily limestone (calcium carbonate $CaCO_3$) and quicklime (calcium oxide CaO) are used for the acid neutralisation process. Prior to use, it is necessary to convert the quicklime to hydrated lime ($Ca(OH)_2$) through a slaking process. This is usually performed on site if reagent consumptions are high. Hydrated lime is also available as a dry product for direct use. In the remote mining areas of northern Saskatchewan, long transportation distances make the use of limestone uneconomical.

Both hydrated lime and limestone are typically fed as slurries, with feed rates controlled by automatic pH monitoring systems. The primary product from the neutralisation of sulphuric acid with a calcium based alkaline is gypsum, produced as a precipitate as follows:

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4.2H_2O + CO_2$$
$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4.2H_2O$$

Gypsum however is prone to supersaturation in the aqueous phase, and may persist in solution at concentrations above its normal solubility. Gypsum formation commonly result in excessive scale formation in piping systems and on monitoring equipment, where, at flow irregularities, seeding and precipitation may occur. Scale formation lead to significant maintenance requirements and in some cases disruption of continuous operation.

Selection of the type of neutralising reagent is further dependent on various chemical and physical implications. Since limestone is a less soluble reagent than hydrated lime, the formation of gypsum on reagent particle surfaces tends to blind the reagent to further reaction, reducing the chemical utilisation efficiency. In addition, the interaction of the carbon dioxide generated during the neutralisation process, and the subsequent processing requirements, both physically and chemically, needs to be considered. The carbonate ion may render some metal species more soluble than in the absence of this ion. Carbon dioxide, attached to particulate solids, may increase their buoyancy, rendering subsequent gravity solid-liquid separation techniques ineffective.

Other alkaline reagents that may be considered for neutralisation include:

1. Caustic Soda (NaOH): usually not considered economically feasible where treatment loads are large. Since most sodium salts are highly soluble, the total dissolved solids load is increased, but, equivalently the total sludge production is reduced. Since this reagent is highly soluble, the utilisation efficiency is high and is characterised by a high reactivity. This reagent may be considered for smaller installations where reagent costs are less significant.

2. Soda Ash ($NaCO_3$): in general similar neutralisation characteristics to caustic soda, but will evolve carbon dioxide with possible detrimental effects as described for limestone. May be used for particular situations where metal carbonate precipitation rather than metal hydroxide precipitation is more effective (e.g. cadmium (Lanouette, 1977) and manganese (Johnson 1982)).

3. Ammonia ($NH_3$): characterised by a high reactivity and a high product salt solubility. Precluded as a viable alternative due to the toxicity of the ammonium ion and the nitrogen contribution to the effluent. The ammonium ion is also a strong complexing agent and may hinder hydroxide precipitation.

4. Mill tailings, fly-ash, etc.: may be alkaline in nature (dolomitic) and may contribute neutralisation potential. However, it is essential to ensure that other undesirable elements are not rendered soluble subsequent to the neutralisation reaction. Addition of these alkalinity sources significantly increases the sludge volume as a result of a reduced alkalinity availability and will impact on treatment plant and sludge storage facility sizing. It may potentially serve to reduce overall reagent costs and alter sludge dewatering and stability characteristics.

In addition to metal hydroxide precipitation, metal sulphide precipitation may be applied to produce highly insoluble compounds that remain stable under non-oxidizing conditions. Metal sulphide precipitation may be achieved with the use of sodium hydrogen sulphide (NaHS), which, upon dissolution, produces hydrogen sulphide. The sulphide ion then reacts with certain bivalent metal species such as copper, cadmium and zinc, to produce the highly insoluble metal sulphide compound.

The performance or efficiency of the precipitation process is a function of the solubility of the precipitate at the prevailing pH and physicochemical conditions, and the effect of pH variation on the stability of the precipitate.

*Uranium*

Technologies for uranium removal include ion exchange, lime neutralization and reverse osmosis.

Ion exchange treatment with a strong-base anion resin has returned 99 percent uranium removal efficiencies from low concentration effluents. Lime neutralisation is less efficient and the concentration reduction efficiency is affected by the presence of carbonate during the precipitation process due to strong anionic carbonate complexing.

*Radium*

Technologies for radium removal include ion exchange, co-precipitation with barium sulphate, lime neutralization and reverse osmosis.

Co-precipitation of radium with barium sulphate as a $Ba(Ra)SO_4$ precipitate has been the standard treatment technology applied for the removal of radium. Due to the fine particle size of the precipitate, coagulation and filtration may be required to reduce radium levels to be acceptable for discharge. Barium chloride is used as the barium source. Reagent addition is performed at a concentration of 10 to 20 percent, made up in low sulphate water to prevent the precipitation of barium sulphate. Commonly barium chloride addition rates vary from 10 to 100 mg/L.

Radium selective ion exchange resins are available from the Dow chemical company. Full scale treatment for the removal of radium has been evaluated elsewhere (Neven 1985), and removal efficiencies of 90 to 95 percent are possible for low concentration effluents. It appears that ion exchange is highly efficient and cost effective for the treatment of low radium concentrations.

Lime neutralization processes require a high pH of 10.5 to 11 for maximum removal. Reverse osmosis at operating U.S. plants has provided high removals (87 to 97 percent) of radium.

*Arsenic*

The standard procedure for arsenic removal is co-precipitation with ferric (sulphate) and calcium as the respective arsenates. Arsenic in solution occurs at two valencies: trivalent and pentavalent arsenic. Since the trivalent or arsenite compounds are more soluble than the pentavalent or arsenates, ferric iron is required to oxidise the reduced valency arsenic to the higher oxidation state prior to precipitation. Chlorine and potassium permanganate may also be used in the oxidation process. The following reaction apply for the precipitation of arsenate with ferric iron:

$$2H_3AsO_4 + Fe_2(SO_4)_3 + 3Ca(OH)_2 \rightarrow 2FeAsO_4.2H_2O + 2CaSO_4.H_2O$$

and with calcium:

$$2H_3AsO_4 + 3Ca(OH)_2 \rightarrow Ca_3(AsO_4)_2 + 6H_2O$$

Stability of the ferric arsenate tends to improve as the iron to arsenic ratio increases. Iron to arsenic ratios of 4:1 are recommended for efficient removal and levels lower than 0.5 mg/L may be achieved.

*Nickel*

The common treatment technology for nickel is lime precipitation at a pH of 9.0. Nickel hydroxide precipitate, may be redissolved if the pH is decreased into the neutral to acid range. Nickel in solution may typically be reduced to less than 0.5 mg/L with lime precipitation. The precipitation of nickel sulphide may present an alternative treatment option to achieve low soluble concentrations with enhanced stability. In the disposal of sludge produced from a sulphide precipitation process, consideration must be given to preventing oxidation and remobilization of metals.

*Thorium*

Thorium solubility decreases significantly for pH values greater than 4.0. Simple lime neutralisation to a pH of 5 to 7 will reduce thorium concentrations to below 1.0 mg/L. Thorium -230 activities in treated discharges in the neutral pH range are typically below 1 Bq/L.

*Miscellaneous Metals*

There are several metals in uranium ores and mine rock that may potentially be released during ARD generation. These include rare earth metals, molybdenum, cobalt, vanadium, lead, copper and zinc. With the exception of molybdenum, lime precipitation to pH 8 or 9 is considered an adequate treatment option. Molybdenum removal is more complex and is usually carried out by co-precipitation with iron within the pH range of 4 to 5, since the sludges are generally unstable in the neutral to alkaline range.

*Sludge Stability and Disposal*

The management of metal hydroxide sludges is a common problem at all acid generating sites where lime neutralisation is being practised. Metal hydroxide sludges are gelatinous, poorly consolidated, have high water contents and occupy large volumes in any disposal area. In addition to the metal hydroxides, these sludges also contain gypsum and may contain various other metal compounds such as arsenates and heavy metal sulphides.

The stability of the sludge is measured by the potential for the contaminants to re-enter the environment. Generally, sludges are stable under the conditions they are produced, and therefore are considered to be stable in the short term. However, instability may occur when the sludges are exposed to air, or contacted with solutions not in equilibrium with the sludge, or when sludge characteristics change over extended time periods as a result of slow chemical reactions occurring within the sludge.

For example, gypsum has a solubility of approximately 2.1 g/L in pure water at 25°C. Potentially high loads of gypsum may be mobilised by water percolating through sludges

produced by lime precipitation systems. Gypsum based sludges deposited to minimise exposure to water flow should minimise the potential for dissolution.

Heavy metal hydroxide solubility increases with a decrease in pH. Similarly, the presence of complexing agents such as cyanide, chloride or naturally occurring organic ions may result in the remobilisation of heavy metals. Also, if sulphides are present in the sludge, acid generation may occur within the sludge, which will result in the remobilisation of heavy metals. Each of these aspects affecting the stability of the sludge have to be considered when deciding on an appropriate disposal site and method. The chemical stability of the sludge can be determined using tests such as those described in Section 5.7.

In a study by the U.S. Bureau of Mines (Ackman 1982) on disposal practice for mine drainage sludges it was found that of 33 operating plants surveyed, 14 disposed of sludges in underground mines, 9 permanently stored sludges in ponds, 9 removed sludges to coal refuse sites and 1 buried sludges on site. For the Saskatchewan situation, deep mine disposal is practical only where truly abandoned underground workings are located. Disposal within the tailings basin may only be practical if sufficient storage capacity is available over the long term. The low permeability and high water content of these sludges may serve as an effective oxygen barrier to potentially acid generation in the tailings. However, such sludge may become susceptible to remobilisation as a result of long term exposure and may therefore require an additional covering layer.

*Adsorptive Extraction*

Several clays, zeolites, hydrous oxides, soils and sediments exhibit strong adsorptive reactions. Because uranium exhibits a high solubility under oxidising conditions and forms strong anionic complexes with carbonate, it is only moderately adsorbed. Thorium is insoluble at neutral pH conditions and therefore readily retained. Radium appears to adsorb readily to clays, soils, and sediments via an ion exchange-like process.

### 6.4.4 Passive Treatment Systems

*Treatment of ARD using wetlands*

Naturally occurring wetlands have for some time attracted interest from the mining community due to their ability to effectively ameliorate acid rock drainage. The treatment of ARD by bogs and marshes has been observed at several locations and some detailed analyses of the response of actual wetlands to acid mine drainage have been carried out, (Wheeler, Kalin and Cairns 1991; Eger and Lapakko 1988). There have not been any specific investigations of the effectiveness of wetlands for the treatment of drainage water from the uranium mines in Saskatchewan (Gormely et al., 1990).

Various studies conducted over the past decade have indicated significant decreases in iron, manganese, magnesium, sulphate as well as other "heavy" metals such as nickel and copper levels with an increase in pH for acidic rock effluents flowing through wetland ecosystems. (Karathanasis and Thompson, 1991). Numerous laboratory simulations of the processes have been carried out, and this has led to the development of artificial (planted) wetlands to treat acidic metal bearing effluents. Interest has steadily increased in these systems due to their low cost, ease of maintenance and efficiency given the right conditions for the biological processes to operate effectively.

Factors influencing the treatment processes are more easily controlled in constructed rather than natural wetlands. Also, increasing recognition of the value of natural wetlands as habitats for wildlife and the need to maintain this habitat in an unaltered state has stimulated interest in the use of constructed wetlands as an alternative to natural systems. (BC ARD Technical Guide, 1989)

Much work is currently being undertaken in this field, and already a number of companies exist in Europe specializing in the "installation" of such wetland systems for various effluent treatments.

The application of wetland treatment to acid rock drainage from mines in Saskatchewan may be limited by a number of factors such as:

- *The short growing season.* The period during which the biological processes resulting in effluent treatment will be active may be limited. Also, the rate at which the processes occur will vary during the growing season, reaching a peak in late August or early September.
- *Climatic conditions.* These may mean that low flows will occur in the winter when the processes are not active while higher flows are characteristic of the summer months when biological activity will be highest. However, the spring freshet with annual peak flows and corresponding high loads will occur when biological activity levels are still relatively low. "Overflowing" of the wetlands may occur unless the area of the wetland is great enough to accommodate these high flows and allow sufficient retention time for treatment. This reduction in efficiency due to high flow rates has been observed at constructed wetland sites, when input and output metal concentrations remained much the same (Karathanasis and Thompson 1991).
- *Contaminant removal.* The removal of readily leachable metals such as arsenic and nickel, and radionuclides, in addition to acidity and metals associated with ARD, must be evaluated. In addition, contaminant uptake in the wetland (or bog) and metal accumulation must be considered.

However, the natural occurrence of large areas of bog in the province may mean that these areas can be utilized for treatment of locally produced ARD. Contaminant loads and their rate of introduction into the natural ecosystems should be carefully calculated to avoid initial damage to the system. Should this occur, recovery may take several seasons and the ecosystem which develops as a result of this damage may show significant changes in species composition. The construction of holding ponds above the bog area to level out flows, or the diversion of the spring freshet to more extensive areas of bog may be possible to avoid "overflow".

*Wetland Treatment Processes*

Amelioration of water quality in wetland occurs as a result of a combination of processes, including settlement of suspended solids due to low velocity sheet flows, sulphate reduction, metal oxidation and a number of other processes taking place in the microphyte root zone at varying depths.

Reducing conditions are produced within the root zone of the wetland, where sulphate reducing bacteria utilize sulphate to oxidise organic matter, releasing hydrogen sulphide ($H_2S$) and bicarbonate ($HCO_3^-$). At pH levels greater than 4, sulphate reduction will occur and $H_2S$ combines with ferrous iron to form iron sulphides.

It has been found that in wetlands, where metal oxidation is the more important mechanism, levels of metal oxides in the substrate reduce with depth while metal levels increase with depth. Metal removal by peat material in the laboratory has been demonstrated with efficiencies of 80 to ±100 percent.

Maximum removal efficiencies for hydrogen, sulphate and iron ions in natural Sphagnum wetlands are reported to be as high as 98 percent, while the efficiency of constructed Typha wetlands can range from 37 to 58 percent.

Factors controlling the treatment processes include the rate of effluent inflow relative to the surface area of the wetland, the gradient of the wetland area and thus retention time and the quantities of free surface water. Other factors include the vegetation type, the substrate and the composition of the ARD.

Experience in bench-scale and some field trial experiments shows that the addition of a carbon and nutrient source may increase wetland efficiency without altering microphyte species composition.

The advantages of wetland treatment systems relative to other treatment technologies are summarized as follows:

- adaptability of wetland systems to acid drainage (pH as low as 2.7) and elevated metals content;
- ability of wetland systems to improve the quality of acid mine drainage is well documented in the northeastern and southeastern, and to a lesser extent in the western United States;
- capital costs of natural wetland systems are relatively low;

- operational and maintenance costs of constructed wetland systems are relatively low;
- wetland systems are generally self sustaining and require little or no ongoing maintenance; and,
- wetland treatment systems also provide additional environmental benefits such as wildlife habitat, flood control and aesthetic improvements.

The following are disadvantages of wetland treatment systems relative to other treatment technologies:

- in mountainous terrain where sufficient flat or gently sloping land is unavailable, capital costs of constructed wetland systems are increased due to earth moving requirements;
- land area requirement per unit flow of water to be treated can be large (typically around 50 $m^2/m^3d^{-1}$);
- treatment during winter is reduced;
- impacts on wildlife are still unknown;
- operating experience is relatively limited;
- behaviour of wetland systems with respect to some of the highly toxic metals found in Saskatchewan mineral deposits is not known at present; and,
- the accumulation of metals in the wetland.

*Biological Sulphate Reduction*

Biological sulphate reduction has been identified as one of the major contributors to the amelioration processes in wetlands. The direct reduction of sulphate to hydrogen sulphide is brought about by specialized strictly anaerobic bacteria and is accomplished by two genera of anaerobic bacteria : *Desulfovibrio* (five species) and *Desulfotomaculum* (three species). These bacteria are all gram negative, heterotrophic organisms and have a respiratory metabolism in which sulphates, sulphites and/or other reducible sulphur compounds serve as the final electron acceptors, with the resulting production of hydrogen sulphide. The organic substrates for these bacteria are generally short chain acids such as lactic and pyruvic acid.

In nature these substrates are provided through fermentative activities of anaerobic bacteria on more complex organic substrates.

The activity of these sulphate reducing bacteria is important not only due to the production of hydrogen sulphide, but also due to the subsequent metal interaction and the increase in alkalinity. Hydrogen sulphide readily reacts, for example, with solubilised copper at low pH values to form the insoluble sulphide mineral. Similarly, the precipitation of zinc is possible provided suitable conditions exist (function for example of solution pH).

Recently, sulphate reduction has been recognised as a potential ARD treatment process in its own right. Natural *in situ* sulphate reduction has been identified in an underground mine in Norway. This presents the potential for instituting a relatively low maintenance biological treatment system in abandoned underground mines, that not only modifies the effluent pH, but also extracts the soluble metal content as stable sulphide compounds. The reducing conditions under which these sulphide metal compounds are deposited, also provides an ideal long term storage facility for the preservation of these compounds.

## 6.5 Current Experience

It is now recognized that the control of the oxidation and acid generation processes, in any significant volume of tailings or mine rock, can best be accomplished by exclusion of oxygen, which is most effectively achieved with a water cover or saturated under water placement:

- voids are filled with water in a saturated mass; therefore, no barometric pumping or advective mechanisms; and,
- diffusion through water is slow.

Acid generation reactions can be significantly slowed in a saturated mass and where, under anaerobic conditions, the acid generation reactions can be effectively limited. Oxygen can be transported through water to the reaction sites by either advection or diffusion. Transport by advection is limited by the solubility of oxygen in water which is typically less than 11 mg/L. Solubility also generally decreases with decreasing temperature. At 10°C the solubility of oxygen in water is $3.6 \times 10^{-4}$ mol/L. The selection and design of the facility can

limit advective flux. Control of diffusive transport is a significant advantage of a water cover, as the diffusivity of water is four orders of magnitude less than air. Canmet-MEND (1989) described the effectiveness of underwater disposal in controlling the release of metals from tailings with reference to several case histories and published documents. Experience at the Skorovas site in Norway (Liseth and Miljøplan, 1991), and the Island Copper Mine in Canada indicate similar control of acid generation for mine rock deposited under water.

# 7.0 MODELLING

## 7.1 Background

The laboratory and field test procedures described in Sections 4 and 5 are widely used for ARD prediction and are continually being updated as the understanding of acid generation and drainage increases. There are difficulties however in that the cost of a detailed evaluation (including field tests) for every site and rock type can be prohibitive. The comparative data, available for the extrapolation of laboratory data to long term field performance, is also very limited. As the understanding of the controlling processes and geochemical reactions develops, more effective testing and modelling procedures are being developed, both to estimate the quantity and evaluate the geochemical nature of mine rock, and also to develop appropriate waste management plans.

Considerable research has been undertaken in recent years on the prediction of acid generation potential and seepage quality from sulphidic mine residues. Mathematical models, such as the RATAP model (Senes and Beak 1988), have been developed for the prediction of acid generation in tailings. Similar models however are not available to predict acid generation and drainage from mine rock piles. While the basic chemistry of the acid generation processes is the same, the factors controlling acid production and drainage quality in tailings differ significantly from those operative in mine rock piles.

## 7.2 Use of Models

Environmental impact is dependent on the water quality at the point of impact. Modelling is used to estimate the nature of such impacts and how they will change with time. Such modelling serves to indicate the evolution of ARD quality and the impact on the environment, and is used to evaluate the effectiveness of alternative control technologies.

Models range from simple spreadsheet models, used for a water balance for an example, to more complex mathematical models for coupled unsaturated/saturated flow. The model output can only be as reliable as the data that is provided, and a more complex model does not necessarily provide a "better" answer. Care must be taken to select a model appropriate for the data and the questions to be answered. The results must be evaluated in the same light.

There are essentially two objectives resulting in two types of modelling for water quality:

- to predict the approximate maximum concentrations, flow rates and chemical loads for the design of a collection system or treatment plant. This type of prediction requires approximate "worst case" estimates for design and sizing of facilities and equipment.

- to predict the short and long-term concentrations and loads that will be released to the environment. This is considerably more difficult as it requires accurate predictions of small loads and concentrations (ppm or ppb level), which are directly discharged into the receiving environment, for evaluation of environmental impact.

One of the limitations of the current technology in both testing and prediction is the time scale at which testing and field monitoring can practically by done. Metal leaching and ARD are time dependent processes and experience in Norway and Sweden has shown that ARD can continue for hundreds of years. The duration of the acid generation must also be predicted to select appropriate control measures and adequately provide for long term monitoring and maintenance. Given the low sulphur content of many of the uranium orebodies in Saskatchewan (less than 2 percent sulphur), the period of active oxidation may be shorter than in higher sulphide deposits. Experience in Saskatchewan has shown that while readily soluble components can appear in solution within hours or days of exposure, the development of acidic drainage from rock piles occurs over a period of months or years. Sampling of pit wall rock however indicates that the initiation of oxidation may occur in a shorter time frame, as paste pH values of less than pH 5 have been detected at working faces in open pits. If the time period is relatively short, collection and treatment may be a necessary option. Due to storage, the flushing of the oxidation products from rock piles may take tens of years longer than oxidation product generation and this must also be considered in the prediction of long term water quality.

Techniques are required to reduce the amount of laboratory testing, and to permit the extrapolation of laboratory and field data to the scale of field volumes and the long term for the estimation of rates of metal leaching, acid generation and associated neutralization and attenuation processes.

The Draft Acid Rock Drainage Technical Guide (SRK, et al., 1989) provides a more detailed discussion of the types of models that are available, the mechanisms or processes simulated, and the selection and development of models. The following discussion is a summary, to provide a basis for selection of an appropriate model and for the design of testing programs.

## 7.3 Types of Models

Modelling is used for a number of specific tasks in the assessment of drainage water quality from mine rock piles:

- evaluation of site hydrology and water balance;
- extrapolation of ARD and leaching prediction laboratory test data to field material quantities and time scale;
- prediction of contaminant migration in surface and subsurface water flows;
- modelling of contaminant load releases and resulting concentrations in the receiving environment, based on dilution;
- evaluation of control options such as cover modelling for air/oxygen transport; and,
- assessment of environmental impact.

A variety of types and complexity of models available for these applications. In general terms the simplest level of modelling is based on observations of field behaviour and empirical calibration of the information to predict future behaviour. The next level consists of laboratory testing of representative samples and extrapolation of the test data over years or tens of years based on either empirical data or mathematical expressions. The most sophisticated models are the complex mathematical models which attempt to predict leaching and acid generation based on a fundamental, theoretical understanding of the underlying processes and controlling factors. The complexity of the models arises from the variety of natural processes which must be simulated, and require different types of mathematical expressions:

- dynamic or time dependent processes such as metal sulphide and ferrous ion oxidation, heat generation and transport, and oxygen diffusion and convection are expressed by differential equations;

- equilibrium expressions are used to represent processes such as solids dissolution, aqueous speciation, neutralization and buffering reactions, ion exchange and surface reactions (adsorption and complexation) and are represented by simultaneous algebraic equations;
- empirical algebraic expressions are used to simulate variables such as seasonal conditions (precipitation, temperature) or for estimation of parameters such as temperature, reaction rates constants (as a function of pH).

Spreadsheet models are often the most appropriate level of modelling for water quality predictions (based on dilution and simple attenuation), or for site hydrology and water/chemical loading balances. These are primarily volume and loading calculations which do not attempt to simulate geochemical processes. For predictions involving geochemical interactions including radioactive decay, soil/water/gas interactions, attenuation and (re)mobilization processes, mathematical models have been developed and several are commercially available. There are a number of commercial and public domain software packages that have been developed for contaminant migration in the surface and subsurface that are well documented in the literature. Mangold and Tsang (1991) provide a summary review of many of these subsurface hydrological and hydrochemical packages. SRK et al., (1989) provides a summary of the development of modelling for ARD prediction.

## 7.4 Limitations

Models must be used carefully, recognizing the sources and extent of uncertainty inherent in the data, the type of model, and the objective of the modelling (environmental impact assessment as opposed to a scoping investigation). The uncertainty arises from a number of factors:

- *Lack of parameter calibration and model verification.* The history of ARD prediction and water quality monitoring is relatively short compared to the time span over which predictions must be made. Therefore the existing historical database is very limited and often insufficient for adequate calibration or verification.
- *Incomplete model structure.* This occurs when attempting to represent complex natural systems, which are only partially understood, with mathematical

expressions or models that are not complete or may not be valid due to oversimplifying or do not recognize the true controlling conditions or rate limiting processes. The converse must also be considered; increasing model complexity does not necessarily improve the predictive ability or accuracy, as more input data is generally required and additional assumptions must be made to develop the model framework.

- *Inherent parameter bias and variability.* Many parameters that are entered into the model are not constant but have a statistical distribution, such as sulphur content, particle size, or climatic data. The use of inaccurate estimates based on biased samples can have a significant effect on the results of the model predictions.
- *Assumptions and lack of input data.* The data input requirements for mathematical models can often be large, varying from approximately 22 input parameters for simple models for pile leaching with oxygen and heat balance simulation (Cathles and Apps, 1975) to 73 for multi-layered models with speciation (Senes and Beak, 1986; SRK et al., 1989). As a result, some models require more detailed input data than is typically available from the testing programs, and assumptions have to be made regarding these values. Testing programs have to be designed to provide the information required for modelling, but for several sites in Saskatchewan, as in other areas, such information is not available for the predictions that now need to be done. Some of this information cannot now be obtained since conditions have been changed and records of the relevant changes (such as a record of mine rock placement) have not been kept.

To be used as predictive tools, mathematical models require verification, calibration, and validation. Verification involves the examination, by an independent expert, of the fundamental equations and the underlying assumptions for correctness. The lengthy, often complex, algorithms must also be checked. The model must also be sufficiently robust to produce consistent results throughout the entire application range of input parameters.

Model calibration refers to the determination of the "best" parameter values for the model. "The measure of the 'goodness of fit' is some statistical property, such as the residual sum of squares between observations and predictions" (SRK et al., 1989). Historical field data, from existing

rock piles, provides the best basis for parameter estimation, however, the level of detail in the database is usually too limited, for example, in many cases drainage water quality monitoring has been done with only quarterly sampling (thereby missing seasonal changes), with limited flow measurements, and analysis only for total metals. The other critical area in which data is generally very limited is the composition of the pile itself. To predict geochemical behaviour from a rock pile, the mineralogical and geochemical composition of the pile must be characterized. It is difficult to interpret the resultant drainage water quality, and design effective controls, without an understanding of the source of the contaminants.

Validation of a model refers to the application of a calibrated model to a "... new set of data collected at a different, but similar location or at the same location at a different time. Due to the general lack of long-term field data, it is unlikely that any model developed for acid generation in waste rock dumps ... is fully validated" (SRK et al., 1989). The similarity of location and setting is important to note as a model cannot be validated for every situation (Mangold and Tsang, 1991).

Recognizing the limitations of the input data to the models, and the limitation and uncertainty of the models themselves, the accepted approach to predictions of environmental impact is to identify a reasonable range of numbers, ie. the probable predicted "best case" and "worst case" and the "normal" or "average" case. Each of these evaluations must be done for the natural range of conditions (eg. high and low rainfall, temperature etc.), and simple, spreadsheet-based software has been developed to allow "what if" evaluations.

## 7.5 Models for Prediction of Drainage Water Quality

The physical and geochemical nature of the dump is determined by the physical configuration, the geochemical distribution (acid producing and acid consuming material), and the transport of air, water, and temperature through the waste rock dump. These components are strongly interdependent. It is not realistic to try to explain the behaviour of the dump with a single mathematical expression each element and its controlling factors must be identified and described by appropriate mathematical expressions and the interrelationships defined to link the elements in an overall mathematical model. It may be viewed as an overall model with a series of sub-models for temperature, air and water movement, oxidation, neutralization attenuation etc. Such

an overall model has not yet been developed, and the current approach is to use laboratory testing to simulate various sub-models together with simple mathematical or spreadsheet models to estimate the contaminant yield from the various source(s) and to predict the impacts.

The generation of acidic drainage within the mine rock pile and the transport of low pH drainage to the receiving environment can be visualized as a series of linked processes or reactors occurring along a large number of flow paths, each of which is a component of the overall model. Fundamentally different reactions occur in each reactor type:

- local oxidation and acid generation occurs at initiation sites within the mine rock pile (local reactors);
- from local reactors is drainage modified by oxidation and neutralization reactions and leaching of stored products as it passes through the underlying mine rock, and there is a progressive development of acid generation along this flow path (flow path reactors);
- mixing of the various surface flows and of the contaminated contaminants occurs along the base of the pile (surface flow reactors);
- subsurface contaminant migration occurs in strata below the pile (subsoil flow reactors);
- biological reactions occur in the downstream environment (environmental reactors); and finally,
- release occurs to the receiving environment at the point of control or impact.

A mine rock pile can therefore be viewed as comprised of a number of components or "reactors" as illustrated in Figure 7.1) which represent acid generation and metal leaching within the pile. Each "string of reactors" represents a flow path through the pile from infiltration entry point to seep exit point. In reality, there may be any number of flow paths. It is convenient to visualize the dump divided in this manner and to investigate the properties, conditions and controls within each reactor and along each string or flow path. The development of such a modelling methodology is in the first phase, sponsored by the B.C. Ministry of Energy, Mines and Petroleum Resources and Environment Canada, and approved by MEND (Broughton and Robertson, 1991).

This understanding of the components or series of processes which control drainage water quality within a rock pile has been implicitly recognized in the current approach to water quality prediction as shown in Figure 7.2, with conventional and modified humidity cell tests used to simulate the acid generation conditions, and column and batch mixing tests used to represent reactions along the drainage flow path.

The following discussion provides a summary of the current state of practice in modelling each of the components. For some areas there has been considerable development and models exist which can be directly applied. Some examples are provided. However for some areas, such as the geochemical reactions within a pile there are no calibrated and verified models currently in standard use. Models or theoretical research which could be adapted, or are of limited application, are listed under "Sources of Codes".

### 7.5.1 Infiltration

The HELP model (Schroeder et al., 1983), the adapted Swedish cover model (Collin, 1987), and other infiltration programs can be used to model the infiltration of water and oxygen entry into the dump. The need to accurately model partially saturated flow represents an ongoing limit of many of the existing infiltration estimating codes.

*Available Models*

- infiltration models such as HELP (Schroeder et al., 1984), requires lab testing of soil moisture characteristics;
- climate/precipitation modelling; and,
- programs such as the TRUST - Kemakta model (Collin et al., 1990), DRAIN, (NHRI, 1989) for evaluation of the effect of covers on infiltration.

### 7.5.2 Dump Characterization

The characterization of the mine rock pile, in terms of the physical properties and geochemical distribution within the pile, is critical to the modelling. The geochemical distribution of materials within the dump will control the distribution of acid generating, readily leachable, neutralizing and inert materials within the dump. Air flow, hydrological regime and thermal regime will be controlled by the distribution of physical properties through the pile. The heterogeneity within

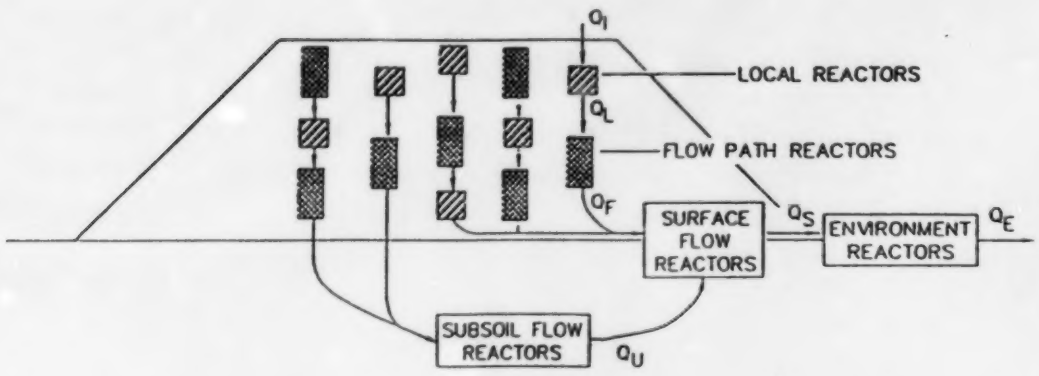



Figure 7.1 Components of Acid Generation and Contaminant Migration

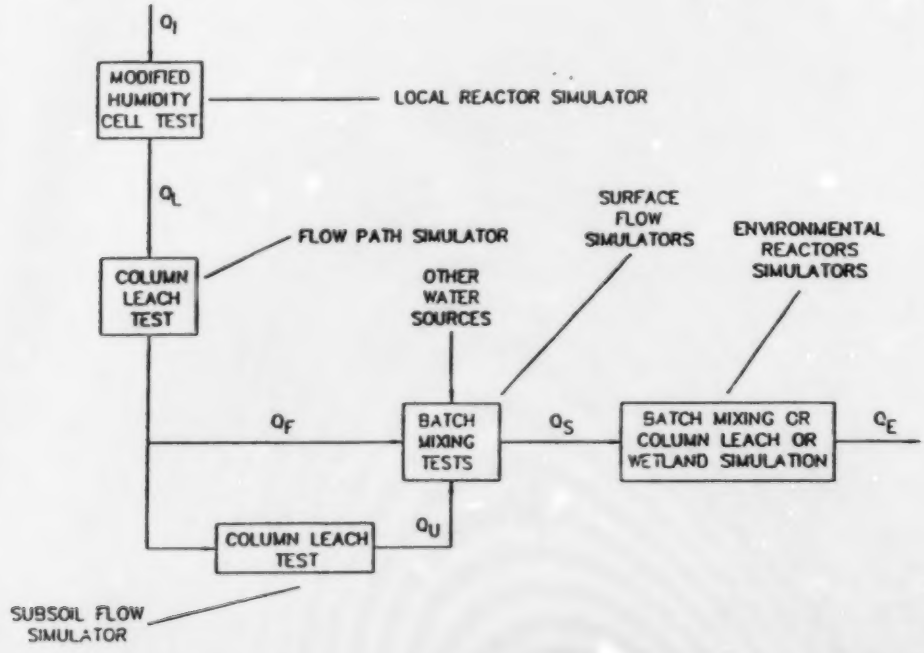



Figure 7.2 Flow Path Simulation Used As Basis for Modelling Drainage Water Quality
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each pile, and variability between piles must be addressed. A geostatistical approach, utilizing ore deposit modelling techniques, issued to address the probable distribution within a pile.

*Available Models*

- physical distribution can be estimated from visual observations, actual measurement of the blasted rock, scaled photography and digitizing of gradation, or formulations such as the Rozin-Rambler equation which allows the prediction of gradation from spacing of holes, etc.

*Sources of Codes*

- a number of orebody block modelling codes using geostatistics are available and are being expanded to include ARD/leaching potentials in the block characterization and adapted to predict the geochemical or mineralogical distribution within a pile and,
- oxygen transport models (Davis and Ritchie, 1986) have been developed, however the effects of convection and barometric pumping, in marginally acid generating dumps are not addressed.

### 7.5.3 Acid Generation

Oxidation of sulphide minerals is initiated in local sulphide reactor zones, throughout the mine rock pile producing acidity, sulphate and dissolved metals. These processes are reasonably well understood within tailings, with relatively uniform sulphide/base distribution, but not within the more variable mine rock pile. To model the rate of acid generation, the effects of each of the following must be determined at the scale of a mine rock pile:

- type of reactive sulphide minerals;
- distribution and exposure of the sulphide minerals;
- type, distribution and exposure of base minerals;
- chemical and biological oxidation characteristics;
- temperature, oxygen and water controls and flux;
- chemical concentration controls.

Generally, the source of the oxidation products and soluble contaminants, and the reactions along the flow path within the pile are not evaluated separately, unless tests are specifically designed to consider the effects of layering by setting up lab testing in a series of cells of columns. The available models which may predict the chemistry are not specific to rock piles, or to marginally acid generating piles.

*Available Models*

- laboratory and field test data extrapolated over time using best-fit line expressions.

*Sources of Codes*

- Jaynes et al., 1984 - based on serial diffusion of oxygen through pore space and reactive core model including biological reactions;
- the principles used in RATAP and UMTAP may be used to develop expressions for the reaction chemistry; however, the physical and geochemical controls on the reactions, and the distribution of materials along the flow path in a rock pile are not addressed in these tailings-based models.

### 7.5.4 Flow Path

Solution flowing through the pile transports the oxidation products from the acid generation site into the underlying mine rock. Acidic solution flowing through a marginally potentially acid producing area rapidly consumes the available base and accelerates the onset of acid generation. However, other reactions along the flowpath can also release readily soluble (without oxidation) contaminants such as uranium and arsenic. The hydrological regime, and particularly antecedent dry periods affect the neutralization capacity of the rock material during wet or "flushing" periods as neutralization potential can be limited by the partial pressure of carbon dioxide, and equilibrium solubility concentrations. This regime also affects the storage of soluble salts during low infiltration and flow periods, both in the acid generator and flow path reactors. Drainage water chemistry within the pile will be controlled by the physical flow model, solute transport and solid/liquid interactions and solution mixing models. Development of a physical flow model is required as there are no models available which address the variable flow conditions which exist in a rock pile.

*Available Models*

- laboratory and field test data extrapolated over time and space using best-fit line expressions.

*Sources of Codes*

- hydrological models (coupled saturated and unsaturated), primarily for unsaturated flow such as SUTRA (Voss, 1984), MODFLOW (McDonald, and Harbaugh, 1984);
- geochemical models such as MINTEQ, which has been used for uranium mining applications, MINEQL (Westall et al,1976), SOILCHEM (Sposito and Coves, 1988), PHREEQE (Parkhurst et al., 1980) and WATEQ4 (Ball et al., 1987), and models which have developed from these.

### 7.5.5 Surface and Subsurface

At the base of the pile mixed stream will form combining flow paths for various portions of the pile. The resulting seeps will have different solution chemistry depending on various stages of development of the oxidation and drainage processes in the various flow paths. The water quality of these mixed streams will depend on solution chemistry and solubility controls. The effect of solid surfaces on solution chemistry along the mixed flow channel is minimized because of the large mass flux of surface water flow, and consequently the solution chemistry is primarily dependent on the chemistry of the component streams.

Subsurface flow and contaminant migration is controlled by a number of physical and chemical parameters which determine drainage quality over time. The potential buffering capacity of solids in the seepage path of the groundwater flow system is much greater than in the surface flow reactors and must be determined. The rate of contaminant plume migration, and changes in solution chemistry, are dependent on the rate and volume of groundwater flux, the neutralising and buffering capacity of the soil, and the contaminant load of the seepage.

A number of codes are available and well documented in the literature.

*Available Models*

- extrapolation of laboratory testing using best-fit line expressions;
- geochemical models as described above; and,
- solute transport and coupled saturated/unsaturated flow models as described above.

## 7.6 Summary

Modelling for prediction of drainage water quality is a necessary tool for preliminary assessments, design and evaluation of control measures and treatment facilities. Models enable the evaluation of a number of options, and can reduce the amount of laboratory testwork required. Some form of modelling is required for any prediction test program, to extrapolate the test results to field conditions and over time to predict short and long term drainage water quality.

There are no available comprehensive models, calibrated and verified for mine rock piles. In many cases simple mathematical models can be used to extrapolate trends from lab and field tests. They are often a more applicable than more complex mathematical models because of the lack of input data and uncertainty associated with the more complex models. A model must be selected to reflect the quality of the data and the objectives of the program; if the data are limited, a complex model may be based more on assumptions than facts.

As the understanding of the fundamental controls and reactions develops, comprehensive, predictive models need to be refined and expanded. Real progress in model verification and calibration can only be realized when a more extensive database becomes available. All current comprehensive models suffer from the lack of sufficient field data for validation.

# 8.0 CLOSURE AND LONG TERM CONTROL

## 8.1 Closure Considerations

There are three objectives in developing a closure plan for the rehabilitation of a mine rock pile:

- protect public health and safety;
- alleviate or eliminate environmental damage; and,
- allow a productive use, to the original condition of the site or acceptable alternative.

There are three types of solutions for the closure of a mine rock pile:

- walk away
- passive care; and,
- active care.

A walk away solution is one where no additional monitoring or maintenance activities are required after the rehabilitation work has been carried out.

Passive care is achieved when there is a minimal on-going need for occasional monitoring and infrequent minor maintenance.

Active care requires that there is an annual on-going need for operation, maintenance and monitoring of the mine site for a long time into the future. This situation would typically apply to the ongoing collection and chemical treatment of acid rock drainage or leachate from mine rock piles. Such a closure plan would require the development of an ongoing operational plan, management structure, and funding.

Mine closure plans should use the best available technology economically achievable. This implies the selection of demonstrated control technology for which the incremental cost of application is justifiable by the resulting environmental protection and does not imply the limit of economic capability of the proponent. This document has summarized the current technology

for sound mine rock management for the control of drainage water quality. The approach is summarized in Table 1.1, reproduced in this chapter as Table 8.1.

The rehabilitation objectives and potential closure measures for physical stability, chemical stability and land use are discussed in the following sections. The Saskatchewan Mine Pollution Control Branch, and Parks and Renewable Resouces are currently preparing "Guidelines for Decommissioning Clean-up and Reclamation of Northern Mine Sites". These guidelines are still in draft form, but must be reviewed and applied in conjunction with the technical suggestions provided in this document.

### 8.1.1 Physical Stability

The main long-term physical stability issue of mine rock and overburden piles is slope stability. There are three forms of slope instability which must be addressed; deep seated slope failure, surface slumping, and surface erosion. Slope instability should be evaluated not only under normal conditions but also under extreme events or perpetual disruptive forces to which they will be subjected after closure. An extensive review of mine rock pile construction methods and potential failure modes is provided in Vandre, 1980, and Piteau Associates, 1991.

Of the three forms of slope instability, erosion of the surface and slopes of mine rock and overburden piles could result in the ongoing release of sediment to the environment and exposure of fresh surfaces to oxidation, infiltration and leaching. Sediment release, through dust or runoff, should not exceed air or water quality objectives for suspended solids. The potential for erosion and sediment release is related to the durability and gradation of the mine rock; durable, coarse rock piles do not normally erode to yield substantial quantities of sediment. Current technology to achieve closure objectives for surface erosion control include:

- contouring of upper surfaces of piles to establish drainage regions and installing ditches with appropriate (rip-rap) erosion protection to drain runoff from the piles; and,

- developing vegetation or constructing rip rap covers to control both wind and water erosion from surfaces.

**TABLE 8.1**

**Summary Guide to Site Assessment and Management Plan Development**

| SUBJECT STAGES IN PLAN DEVELOPMENT | APPLICABLE TO: NEW MINE | EXISTING MINE | CLOSED MINE | APPROPRIATE SECTION OF GUIDE |
|---|---|---|---|---|
| Understanding of Acid Generation | ● | ● | ● | 1,2,3 |
| Understanding of Metal Leaching | ● | ● | ● | 1,2,3 |
| Definition of Pre-development Environment | ● | ● | O | 7.1 |
| Definition of Development | ● | ● | ● | - |
| Site Assessment - Field Investigations | • | ● | ● | 4 |
| Contaminant Release Prediction | | | | |
| - ARD | ● | O | • | 5 |
| - Contaminant Leaching | ● | O | • | 5 |
| Control Measures Selection and Design | | | | |
| - Subaqueous deposition | ● | O | • | 6.2.4 |
| - Covers | ● | ● | ● | 6.2.3 |
| - Others | O | O | • | 6 |
| Modelling | ● | ● | O | 7 |
| Closure Plan Preparation | ● | ● | ● | 8 |
| Monitoring | | | | |
| - Surface water | ● | ● | ● | 9 |
| - Groundwater | O | ● | ● | |
| - Mine rock/tailings | - | ● | ● | |
| - Sediments | • | ● | ● | 4.3.6 |
| - Biological | ● | ● | ● | 4.3.7 |
| - Seeps | - | ● | ● | 4.3.2 |
| - Control Structures | - | ● | ● | |
| - Climate | ● | ● | ● | |

Key: ● Required at comprehensive level.
O Generally required at intermediate level.
• May be required; usually at low or intermediate level.

Where erosion cannot be controlled due to technical or economic factors, then provision should be made for runoff collection and sediment removal in settling ponds prior to release to the environment. The long-term maintenance and operation of the sediment ponds must be addressed.

### 8.1.2 Chemical Stability

The objectives for the chemical stability of rock and overburden piles is to control the release of contaminants to the environment so that applicable ground and surface water quality criteria are not exceeded. Potential chemical stability issues of rock and overburden piles include release of nutrients such as nitrates (explosives residue), leaching of metals, and acid rock drainage (ARD). Generally, nutrients are not a problem after mining has ceased and this would only need to be addressed in nutrient sensitive environments. The principle issues of chemical stability are leaching of metals and ARD.

The measures for controlling acid generation and metals leaching have been discussed in Section 6, which, in order of preference are: preventing the reactions, inhibiting the migration and, collecting and treating the contaminated drainage. Generally it is necessary to address average precipitation conditions, high loading events due to flushing of accumulated acid products during storm events, and low dilution conditions during dry periods.

### 8.1.3 Land Use and Aesthetics

The land use issues of rock and overburden piles include: covering of productive land, changes in topography, surface use, and visual effects. The objectives of the closure plan is to return the area to the original or equivalent land use or alternative use which meet the criteria outlined in Section 4.4. The rehabilitation required for a mine rock pile shall be determined by considering several factors:

- the naturally occurring physical hazards;
- the level of environmental impact; and,

- the expected post-operational use of the land and the productivity of the land surrounding the site.

**In its closed out condition, the rehabilitated mine rock pile should be compatible with that of the surrounding lands, to the extent possible.**

Measures which may be used to achieve this objective include re-contouring, covering the piles with topsoil and overburden, and the establishment of vegetation. Where rock and overburden piles are contoured for aesthetic reasons the final shape should blend into the natural topography of the area to the extent which is practicable.

Resloping and soil covers are readily placed on the upper surfaces of piles. Placement on side slopes usually requires resloping to 3:1 horizontal to vertical.

Given the naturally low land usage in the areas of Saskatchewan uranium mining the requirements for rehabilitation are limited.

A phased vegetation program progressing to climax vegetation is usually required. There are typically three phases in a vegetation program: grasses, transition vegetation, and climax or self-sustaining vegetation. Once the first phase is established the latter phases will develop naturally. Vegetation established on piles may take up metals from the underlying materials in sufficient quantities to be of concern regarding bio-accumulation in browsing or other animals. Where such accumulation occurs, it may be necessary to provide for thick soil covers (see Section 4.3.3) or to fence piles to restrict animal access.

## 8.2 Selection of Options

The success of any control measure is dependent on its ability to abate ARD and/or contaminant leaching and also to resist the action of natural disruptive forces. The suitability and long-term performance of any control measure is a function of its long term stability. Certain control or abatement measures have a limited period of effectiveness, and require constant operation or maintenance to achieve the control objective.

The evaluation of available control options must consider the long-term performance, risk of failure, consequence of failure, environment impact and cost of each option. In many projects the most suitable option is readily apparent. In more complex situations where more than one option is available, and it is not readily apparent which of these is most suitable, all the relevant factors need to be considered in the evaluation of the options. It is important to be able to identify the risk associated with each control measure and to evaluate the available options in terms of both risk and cost.

### 8.2.1 Long Term Performance of Control Options

Mine rock piles can usually be designed to adequately achieve the design and decommissioning plan objectives at the time of close-out. However, in the long term, the mine rock pile and its control structures are subject to two classes of disruptive forces:

- short duration extreme events such as floods, fires, earthquakes and tornadoes which apply forces to the structures in excess of values for which they were originally designed; and,
- slow but perpetual action of forces which bring about deterioration, such as water and wind erosion, frost action, the weathering and chemical change of rock material covers, liners or structural materials, and intrusion by roots, animals and man.

Under the action of these forces, failure is inevitable, given sufficient time. Periodic maintenance can serve to repair the ravages of many of the perpetual forces. For a well designed facility, the required interval between maintenance may be decades or centuries, imposing minimal costs on future generations. Remedial measures may be required after extreme events. The level of periodic maintenance and risk of remedial action which may be appropriate to pass on to future generations must be balanced by the present value to society of the resource. It is necessary to document the required maintenance and schedule in detail to assist in alternative optimum selection and for the benefit of future generations.

A detailed discussion of extreme events and perpetual disruptive forces is presented in SRK et al (1989).

### 8.2.2 Risk of Failure

Probabilistic analysis is becoming an increasingly popular tool for assessing the environmental effects and risks associated with waste management. Risk assessment can be used in evaluating mine projects proposed in environmentally sensitive areas where the consequence of failure is severe. This technique would not normally be used for assessing low impact risks. Various levels of risk assessment may be applied, ranging from simple qualitative studies to identify areas that require special attention, to detailed quantitative studies which allocate a probability of occurrence to specific events.

It is necessary to consider not only probability of failure but also the consequences of failure. The concept of "risk" and "hazard" need to be considered. Hazard simply exists as a "source of danger". Risk includes the likelihood of conversion of that source into actual delivery of loss, injury or some form of impact. As a matter of practical reality risk can never be brought to zero, however, risk may be kept as small as desired by increasing the safeguards.

It is necessary to assess the risk of failure of ARD and/or contaminant leaching control options to identify those options associated with high risk, to evaluate the cost versus benefit of different options, and to suitably design and maintain the selected control measures. The environmental risk and consequences of mine rock management, may be evaluated by means of risk assessment studies.

### 8.2.3 Methodology for Evaluation of Options

The lack of reliable, accurate technology for the prediction of acid generation, the effectiveness of abatement measures and the long-term changes, makes the evaluation and selection of the most advantageous measures more difficult. Much of the assessment methodology is necessarily based on judgement rather than deterministic analysis. In a recent study for the abatement of ARD and/or contaminant leaching from a mine rock pile, an assessment method proposed by Robertson (1987) was used which considers each of the following factors:

- practicality of implementing the measure;
- durability (life expectancy) of the measure;

- security/risk of failure;
- environmental impacts of constructing the measure;
- construction complexity and duration;
- inspection and maintenance requirements; and,
- effectiveness in reducing ARD.

An example of the assessment technique is shown in Tables 8.2 and 8.3 reproduced from the B.C. Acid Rock Drainage Technical Guide.

For each alternative abatement measure a point score was assigned for each of the above factors using a five point scale. The point score for each factor was weighted according to the importance of the factor and the total points counted. This point count was used to rank the various alternatives. By dividing the cost estimate for each measure by the ranking points, a measure of the cost/benefit is obtained. Some of the abatement measures, such as diversion ditches, have a comparatively large benefit at low cost, even though they are individually not capable of reducing ARD to low levels. Such measures are of particular benefit where funds available for abatement are very limited, and they should be considered as part of any ARD abatement plan. The ranking procedure can be used for the selection of the most advantageous alternatives, which can then be investigated and evaluated in greater detail.

It should be the objective of all ARD abatement plans to reduce monitoring and maintenance to a minimum commensurate with the available technology and long-term cost. The current state of the art of long-term ARD abatement is that a condition of no monitoring and no maintenance may not be achievable, even at very high cost, for some of the existing mine rock piles. The perpetual forces of erosion, weathering, root action, frost action and burrowing activities of biota as well as a host of lesser effects, will result in disruption of abatement measure with time. To avoid the detrimental effect of these disruptions, it is considerably more cost effective to provide for a measure of maintenance, rather than to attempt to construct structures that will operate without maintenance, in perpetuity.

**TABLE 8.2**
**Abatement Option: Synthetic Liner Option - Acid Abatement Alternatives Ranking System**
(After Robertson, 1987)

| CONSIDERATION | DESCRIPTION | SCALE | | | | | WEIGHTING FACTOR | POINT TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1 Practicality | Technical Feasibility: | Low<br>1 | 2 | Medium<br>3 | 4 | High<br>5 | x4 | 20 |
| 2 Durability | Years:<br>Life Expectancy: | 1<br>1 | 10<br>2 | 50<br>3 | 100<br>4 | >100<br>5 | x4 | 20 |
| 3 Security/Risk | Risk of Failure | High<br>1 | 2 | Medium<br>3 | 4 | Low<br>5 | x4 | 12 |
| 4 Environmental Impacts | Adverse impacts due to construction or operation:<br>a) Construction<br>b) Operation | High<br>1<br>1 | 2<br>2 | Medium<br>3<br>3 | 4<br>4 | Low<br>5<br>5 | x1<br>x1 | 4<br>5 |
| 5 Construction | a) Complexity, magnitude<br>Months:<br>b) Duration of construction | Maximum<br>1<br>>6<br>1 | 2<br>4-6<br>2 | 3<br>2-4<br>3 | 4<br>1-2<br>4 | Minimum<br>5<br><1<br>5 | x2<br>x1 | 6<br>3 |
| 6 Inspection and Maintenance | a) Frequency of Inspection<br>b) Level of maintenance | Weekly<br>1<br>High<br>1<br><75 | Month<br>2<br>Moderate<br>2<br>75-90 | Quat.<br>3<br>Low<br>3<br>90-95 | Ann.<br>4<br>V.Low<br>4<br>95-100 | >Ann.<br>5<br>None<br>5<br>95-100 | x1<br>x5 | 4<br>20 |
| 7 Effectiveness | Reduction of Contamination | Less secure<br>0 | 2 | 3 | 4 | More secure<br>5 | x10 | 40 |
| TOTAL RANKING POINTS | | | | | | | | 124 |

$$\text{Cost/Benefit} = \frac{\text{Preliminary Total Estimate}}{\text{Total Ranking Points}} = \frac{\$820,000}{124} = \$6,612/\text{Point}$$

**TABLE 8.3**

**Option Ranking According to Total of Ranking Points**
(After Robertson, 1987)

| PROBABILITY OF SUCCESS | RANK | POINTS | OPTIONS | COST BENEFIT $/POINT |
|---|---|---|---|---|
| High Probability of Success (>95% Reduction) | 1 | 124 | Synthetic Liner | 6,612 |
| | 2 | 97 | Chemical Treatment | 11,948 |
| Moderate Probability of Success (75-95% Reduction) | 1 | 103 | Compacted Till Cover | 2,720 |
| | 2 | 87 | Removal of Pyritic Waste to Lakes | 13,655 |
| | 3 | 82 | Alkaline Trenches | 10,609 |
| | 4 | 79 | Waste Removal and Mixing | 17,632 |
| Low Probability of Success (<75% Reduction) | 1 | 75 | Diversion Ditches | 367 |
| | 2 | 73 | In-Situ Seep Neutralization | 1,643 |
| | 3 | 70 | Surface Application of Limestone | 12,471 |
| | 4 | 62 | Limestone Barriers | 6,532 |
| | 5 | 57 | Topsoil and Revegetation | 4,052 |
| | 6 | 56 | Wetland | 8,503 |
| | 7 | 40 | Peat | 6,562 |
| | 8 | 36 | Woodwaste | 12,471 |
| | 9 | 34 | Bactericides | 21,617 |

# 9.0 MONITORING

Environmental monitoring is needed for effective evaluation of the impact of mine activities on both the local and the regional environment. The main objectives of monitoring programs for drainage water quality are to define the baseline or pre-mining conditions, and to monitor the effectiveness of prevention, control or treatment techniques, and to evaluate the long term success of these activities (SRK, et al 1989).

The most important potential environmental impacts as a consequence of the development of mine rock and special waste dumps, result from surface runoff, infiltration and seepage through these piles into surface and groundwater systems, and from wind-borne dust. Other effects include disturbance of wildlife habitat, disruption of drainage patterns, loss of aesthetic quality, and changes in land use.

Water is the primary transport mechanism of contaminants from a site, and the aquatic environment is considered one of the most sensitive components in the discharge environment. Regulations therefore tend to focus on water related issues. Saskatchewan Environment and Public Safety, Mines Pollution Control Branch, has prepared a document that should be used as the basis for all environmental monitoring programs, "Environmental Monitoring Guidelines (For Operational Monitoring at Uranium and Gold Mining and Milling Operations in Saskatchewan) "(Sask. MPCB, 1989). This chapter will discuss only the approach to developing a monitoring program for rock piles.

## 9.1 Approach

There are two general approaches to monitoring:

- regular monitoring, including licence or compliance monitoring; and,
- periodic monitoring and field investigations conducted to address specific problems.

The approach to monitoring depends largely on the application and objectives of the program which may include:

- determining baseline or background conditions;
- early detection of ARD or developing contaminant migration;
- identifying ARD "hot spots" at older mine sites;
- assessing site specific factors controlling ARD;
- evaluating control measures;
- determining environmental impact assessment; and,
- confirming that regulatory standards have been and continue to be achieved.

These objectives will vary depending on the stage of operation (ie. exploration versus closure), and the nature or level of concern with the site, that is, the sensitivity of the receiving environment to the contaminants that may potentially be released. The site specific requirements will ultimately determine the type of monitoring program required.

In the exploration or pre-mining phase, baseline monitoring defines existing physical, chemical and biological environmental conditions of the area. Areas which are particularly sensitive to changes in environmental conditions, or specific contaminant releases can then be identified. Baseline surveys also provide the information required during operation to determine if changes or impacts have resulted from rock pile drainage water.

Testwork should be conducted during this phase to identify materials which are potentially oxidizable or sources of leachable contaminants. The mine and mine rock management plans can then be adjusted to implement control or treatment measures to control drainage water quality.

For an existing operation, the available baseline data is often limited, and background data must be used. Background monitoring, which refers to sampling outside of the areas of influence of the mining activities, should be conducted throughout operation. Generally these sites consist of monitoring stations upstream of the site and the drainage later affected by the rock piles. These data can be used to estimate the original or "natural" condition of the site.

The monitoring program that is implemented during operation and after closure is based on the baseline or background data. Monitoring stations must be located in or near all environmentally sensitive areas which are potentially affected by the development of the rock pile, including both surface water and groundwater stations. Both the rock pile drainage waters, and the receiving

waters must be sampled. It is important that the monitoring program be designed to detect changes in the environmental conditions at each station, to indicate the development of potential drainage water quality problems. Changes in drainage water quality may also result from changes in the characteristics of the mine rock or the deposition technique. Should a change be detected then the frequency and extent of monitoring and analysis should be increased temporarily to confirm the presence, source, and spatial extent of the change. If an adverse impact is determined, control or treatment techniques should be developed and implemented. The monitoring program should be revised to monitor the success of the new techniques.

Towards the end of the mine life, a long-term monitoring program for closure should be defined to reflect areas of environmental sensitivity and evaluation of control measures. The frequency of the monitoring program implemented during and after closure would decrease as the time after closure increases, provided monitoring results indicate that control measures are performing as designed and the risk of contaminant releases are decreasing. The monitoring program must also reflect the regulatory requirements for closure, maintenance and bonding requirements.

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